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The role of the barretter in microwave power measurement

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IN

MICROWAVE POWER MEASUREMENT

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THE ROLE OF THE BARRETTER IN MICROWAVE POWER MEASUREMENT

by

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PREFACE

This work was undertaken during the writer's third year at the United States Naval Postgraduate School. It was written as a result of the writer's interest in the various techniques of microwave power measurements.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

THE ROLE OF THE BARRETTER IN MICROWAVE POWER MEASUREMENT

I. INTRODUCTION

The microwave region has been variously defined, but has generally been limited to the short wave length end of the electromagnetic spectrum. The region embraces a frequency band of from 1000 mcs to near 100,000 mcs, just short of the infra-red portion of the optical region.

Microwave wave lengths, roughly 0.5-30 centimeters, are identical with the range of dimensions of most laboratory apparatus; it is this factor which causes the separation of the microwave region from the regions of longer wave length. Circuits operating at these frequencies are made up of transmission lines, velocity modulated tubes, etc., because components normally used at longer wave length would have to be much too small for practical application. Conventional vacuum tubes cannot be used, not only because the lead wires are too long but also because the electron transit time between electrodes begins to compare favorably with the period of one cycle. As the frequency of operation has increased, the quantities that are useful to measure change. Microwave quantities may be characterized by three "dimensions", power, length, and frequency. All microwave measurements may be reduced to measurements of these three parameters.

In the search for improvements in microwave oscillators, for better methods of microwave transmission, and for measurements techniques in general, the need for an accurate means of determining absolute and/or relative power in this region has become urgent. In the audio frequency region, it is customary to measure voltage or current; in the i-f and r-f regions both voltage and power measurements are common. The communications industry has shown a preference for power measurement on the basis that power is a more convenient and a more meaningful quantity to measure because the specification of power is independent of the characteristic impedance of the transmission line. In the microwave region the measurement of power is one of the few fundamental electrical measurements which can be made; in wave guides, for instance, voltage and current are ambiguous quantities that cannot be uniquely defined. Besides, voltage and current meters for these frequencies are extremely difficult if not impossible to construct.

The amount of energy radiated precludes the use of open wires to conduct microwave currents; this necessitates the substitution of coaxial conductors and hollow pipe wave guides to prevent or reduce the undesired radiation. Emphasis is shifted from the currents flowing in the conductors to the electric and magnetic fields transmitted through the "pipes". The circuit elements take the form of obstacles placed within the transmission lines, and the resonant combination of a coil and condenser at low frequencies is replaced by a resonant cavity in the microwave region. Consequently, the electrical and mechanical problems involved preclude the use of practically all measurements methods employed at lower frequencies. It has been necessary, therefore, to devise new instruments which will provide accurate data for further microwave developments.

Since the techniques of power measurement common at lower frequencies do not lend themselves to the measurement of microwave power, other methods and principles must be used. At present, the fundamental principle of most power measurements in this region involves the conversion of r-f energy to some other form of energy whose effects can be measured easily, quickly, and accurately. Usually, the most practical energy conversion results in heat. Measurements may be made of changes in temperature, thermoelectricity, expansion, resistance, light output, etc., as a result of the heat produced in an r-f power absorbing unit by power dissipated in the element. Any instrument which detects changes in any of the aforementioned quantities in the power absorbing unit may be calibrated in r-f power units and used as a microwave wattmeter.

Power measurement techniques and equipment vary considerably with the level of power to be measured. For this reason, it is convenient to divide the scale of average power into 3 arbitrarily defined regions; high, medium, and low level power. Powers greater than 1 watt are classed as high level power; the range from 10 mw to 1 watt is referred to as medium level power; 10 mw and less of power lie in the low level range. In high level power measurement, assuming the conversion of r-f power to heat techniques, it is customary to make a calorimetric measurement of the thermal energy, using either liquid or gas as the calorimetric fluid. With low power, thermal energy is usually used to effect a resistance change or generate a thermal emf, either change being mensurable according to well-known d-c or a-f procedures. Medium level powers lie in the range for which there are no accurate or commonly used absolute meters. Measurements at this level may be made by use of attenuators or directional couplers which reduce the power to a level which may be measured by low level instruments. The resistance element or thermocouple which is physically small enough to avoid trouble from variations in skin depth with frequency is too small to dissipate high power without suffering burnout. Conversely, the calorimetric technique is unsuited to lower power measurement because of the difficulty of making a simple yet accurate determination of a very small temperature rise. In some cases, indirect power measurements may be made by calibrating r-f voltage indicators such as crystals or gas discharge tubes with an absolute r-f wattmeter of the energy conversion type. Other less commonly used techniques in microwave power measurement involve the conversion of power into light, as in a lamp filament, for example, and the use of diode rectifiers.

When using any power measuring device at these frequencies, there are several factors which cannot be overlooked. Since no wattmeter energy transformer can be designed which is purely resistive over all the microwave band, tuning devices must be used to match this line termination to the transmission line characteristic impedance at any one particular frequency or narrow frequency band. Care, therefore, must be taken that the proper termination is used for the frequency band under consideration, or serious measurement error will result from the standing waves set up by a mismatch. The energy transformation device is relatively frequency insensitive in that r-f energy of whatever frequency reaching it is converted into heat energy. Thus, unless harmonic frequencies are suitably suppressed by filter action, the power indicated will be more than that of the fundamental, normally the only frequency of interest. Since the energy transformers match the characteristic impedance of the transmission line to obtain negligible reflections, the power measured is that of which the source is capable and is not necessarily that power which reaches the normal load (antenna, etc.). The load impedance match for various reasons may be poor, resulting in high VSWR and a change in the power level. Microwave monitoring wattmeters are subject to a somewhat similar error since ordinarily these instruments record only that power going toward the load, the sampling being done by some form of directional coupler. Since microwave power is often pulsed, it becomes necessary to differentiate between "average power" and "pulse power". Both are time averaged values, but differ with respect to the time interval involved in the averaging. If the power is averaged over the duration of a single pulse, the average is called "pulse power"; "average power" is the power averaged over a period of time very large compared with the duration of a single pulse and with the time interval between successive pulses. Pulse power is, thus, always greater than average power except in the limiting case of unpulsed c-w operation where each becomes equal to the other and to the average power per cycle of operation. There is no confusion regarding the pulse length of a retangular pulse; for a trapezoidal pulse, the pulse length is customarily specified as the time interval between the leading and trailing edge half altitude points. Available power detectors respond to and indicate average power, so that pulse power must be calculated; the relationship is

$$P_o = \frac{P}{\tau}$$

where "P_o" equals pulse power, "P" equals average power, and "τ" equals duty cycle (pulse length in seconds times repetition rate).

Since there is as yet no standard technique of power measurement, all meters give readings the accuracy of which is dependent upon the care and skill in construction and calibration. The validity of calibration is dependent upon the premise that all the r-f power is converted into measurable thermal energy in the usual standard, a calorimeter type wattmeter. A theoretical discussion of the equivalence of the effect of d-c and r-f power upon bolometer resistance will be presented in a later section. It must be repeated that there are as yet no absolute standard techniques of power measurement in the microwave region. The government laboratories and various commercial concerns are currently engaged in the research into and the development of microwave power measuring devices and standards.

In the second chapter of this paper a brief survey of the various techniques and instruments for power measurement is presented. A major portion of the paper is concerned with the principle and application of the barretter developed by the Sperry Gyroscope Company in their microwave research laboratory.

II. MICROWAVE POWER MEASURING TECHNIQUES

All of the various and sundry forms of power measuring instruments cannot be presented in a paper of this length. Attempt has been made, however, to present a representative cross-section as well as a historical review of the techniques.

1. Calorimetric Wattmeters.

For measurements of higher powers, a calorimetric method involving the absorption of the available power in a stream of fluid flowing at constant speed is to be preferred. Calorimeters are useful primarily as laboratory tools; the required equipment is bulky, measuring procedure is slow, and the minimum power that can be measured is a few watts. They are used as standards of comparison in the calibration of other wattmeter types and to measure large amounts of power, but their application is limited.

The ideal load element would combine small physical size and sturdy construction, with an electrical design resulting in an input impedance that is a real quantity, constant in value over the frequency range in which measurements are desired. It is possible to realize this goal to a practical degree with 2 general types of load elements. In the first, energy is dissipated in a lossy material and the resultant heat is transferred to a fluid coolant outside of the influence of the high frequency field in which it can be measured. Water cooled carbon resistances or lengths of "lossy" cable are examples. In the second, the electrical energy is converted to heat directly in the liquid which forms a dissipative medium. Such circuit elements find uses other than in connection with power measurement, particularly as broad band terminations, since water loads are relatively insensitive to ambient temperature changes. The time required to obtain a temperature equilibrium with a given power dissipation in a volume of water which is moving at a fixed rate is a function of the length of the line. In general, the shortest length of water line which will give adequate power attenuation should be used.

Fundamentally, it might be thought that the first method has advantages, in that the adjustment of the load impedance may be carried out without affecting the fluid cooling system, while in the second procedure the fluid system forms the absorbing impedance and must be correctly adjusted as an r-f impedance. The second system, however, is easier to construct, and, since the transformation from r-f energy to heat energy is accomplished in the fluid itself, the temperature of the fluid is quick to respond to any change in r-f power, and maximum reading speed is obtained; this system has, thus, come to be almost universally used in the measurement of high level microwave power. The fluid used in the cooling system is generally water, since it is an ideal calorimetric fluid; ordinary tap water exhibits sufficient loss in the microwave region to form an acceptable load material. The water load, together with any impedance transforming elements and temperature measuring devices, is known as a calorimeter.

The first calorimetric microwave wattmeters were designed for coaxial transmission lines at comparatively low frequencies of a few thousand megacycles and operated at a fixed frequency. In an early 10 centimeter band load, a dielectric window was cemented across the line to retain the water circulated through the terminal end of the coaxial container; impedance matching was effected with a pair of stub tuners. This design was not used very long because it represented many of the faults which must be avoided in calorimeter design. Changes in power level having a period of less than 1 minute were difficult to follow because of the large load heat capacity. The impedance-matching operation required up to 5 or 10 minutes; in addition, the tuners were extremely lossy if the shorting contacts rested at a current loop in the stub line. Heat dissipation was non-uniform, being maximum at the input end. This construction permitted free heat interchange with the surroundings and dead pockets in the liquid flow pattern. Dielectric breakdown across the window occurred at relatively low pulse power levels.

Another device for use in this same frequency band and incorporating many improvements in design, but still requiring tuning for each measurement, is known as the "Resonant Chamber Calorimeter". The power from the coaxial cable is fed through a probe exciter into a hollow cylindrical chamber resonant in the E_{01} mode. A tuning piston in one end of the chamber carries a constant flow water column; the water column consists of 2 concentric glass tubes, the outer tube for incoming water and the inner for water return, projecting into the chamber along the axis of the cylinder. The power is absorbed in the water column, the temperature rise of which is measured with thermojunctions mounted on the outer side of the tuning piston. Adjustment of the overall impedance of the calorimeter, so that the impedance of the water column is correctly transformed at the calorimeter input terminal, is effected by use of 2 tuning pistons, one at each end of the calorimeter. Precautions are taken to prevent heat conduction by insulation of (1) the water column from the chamber wall and (2) the chamber from the atmosphere. In order to prevent leakage of power by wave guide transmission, the size of water column pipes is kept to a minimum. A number of lengths of thermocouples insulated from each other are used in series in both the inlet and outlet water tubes; the heat conduction from water to couple is rapid. This instrument is capable of measuring mean powers between 10 and 300 watts mean; the response of the whole system is such that a steady reading may be obtained in a few seconds from switching on after completion of tuning. Owing to the low head losses, a high accuracy of measurement is obtained, being of the order of 5 percent.

The next step in calorimeter design is broadbanding to eliminate the use of tuning controls. There are several schemes for achieving this aim, only a few samples of which will be presented here.

Where matching over a frequency range not greater than about 5 percent is required, a "plate transformer" type of calorimeter has been used. The description of use with a wave guide is given, the application to coaxial type line being similar. A section of guide is closed at one end and filled with water, the water being sealed off at the power input end by a dielectric plate of such a thickness and with such a dielectric constant that it operates as a quarter wave transformer between the air and water filled sections of line. Mycalex with an ϵ_1 of about 6.5 is such a suitable dielectric. The water flows into the guide near the dielectric plate and is removed at the end of the guide; the same system of temperature measurement may be used as in the first wattmeter described.

If wider frequency band operation is desirable, the quarter wave transformer type cannot be used, since the dielectric plate will not act as an impedance matching device over a very wide range. An alternative is a transmission line into which losses are introduced at such a rate that the wave impedance is not significantly affected, and the amount of reflected energy present at the input to the attenuating section is negligible. In one example of this type, the losses are introduced by a column of water of small cross section passing down the side of a wave guide at a position where the undisturbed field strength is small. The glass or quartz tube carrying the water is shaped somewhat like a hairpin but the bend is tapered to a point, in order to minimize reflections at the point at which the incident wave meets the water column; the "hairpin" is mounted parallel to and close to a narrow side of the wave guide. The guide is closed at the end by a shorting plate through which the water tubes pass; the water column is approximately 4 wave lengths long and in 3 centimeter and smaller wave guides may be supported from the short circuiting plate. At 10 centimeters, it is necessary to support the tube with dielectric vanes which decrease the working bandwidth.

One of the latest types of wave guide water load is a design based on the principle of the branched guide directional coupler. A glass enclosed water column is contained in an auxiliary wave guide section coupled to the main wave guide by a linear array of 14 rectangular openings in the broad side common to both sections. If the main guide narrow dimension is gradually reduced to zero by a linear slope of the wall opposite the openings in the main wave guide the power coupled out per opening can be maintained constant. This design has considerably less microwave power loss by radiation than many other types because of the long length of the water column enclosed by the metal shield around the load.

There are several methods of calibration of the calorimeter type wattmeter. In one method, the change in temperature of the water is accurately measured and, knowing the flow rate, the power is calculated from the formula:

$$P = 4.18\ mc_p \Delta T \text{ watts}$$

where "m" is the flow rate (grams/sec.), "c_p" is the specific heat of the water (calory/gram degree C) and "ΔT" is the rise in temperature.

Several techniques for measuring the temperature change in the water have been pursued. The most fundamental, or "brute force", method is simply that of using a thermometer at each end of the water column at the load. The most common use has been made of the thermocouple, however. The junctions of the thermopiles may be immersed in the flow stream or mounted on the outer surface of sections of the flow line. On occasion, thermistors have been substituted for the thermopile. Two thermistors, one in the input stream and a second in the exhaust stream, comprise 2 adjacent arms of an extremely sensitive bridge circuit.

A second system of calibration involves the use of a heater coil located in the flow stream just ahead of the water load. Before each series of measurements 60 cycle power dissipated in the coil is used to calibrate the temperature rise meter. If a meter sensitivity control of the decade type is used, full scale deflection of the indicating meter may thus be made to correspond to any desired power level. The meter is designed to be linear with power, permitting this type of calibration. This method avoids the necessity for precise measurement of temperature change or flow rate, but the latter must remain constant. No calculations of power need be made since an accurate a-c wattmeter measures the 60 cycle power at full scale.

The restriction to measurement of powers of at least a few watts has been primarily due to inability to measure small temperature rises and the relative insensitivity of the entire system at low power levels. A method of absolute power measurement has recently been reported by the Naval Research Laboratory which uses an extremely low loss calorimeter having a sensitivity of about 5 microwatts with an accuracy of 2 percent at levels above 100 microwatts. This technique gives promise of being an extremely accurate one for the calibration of low level meters. It is expected that more complete details as to operation and physical makeup of this instrument will be published soon.

An interesting variation on the calorimetric technique has been developed by the Radio Corporation of America. The wave guide termination is a cavity resonator filled with ammonia gas. The gas not only dissipates the microwave power but is used as the thermometric substance in a gas thermometer. The temperature rise is calculated from the change in pressure; the power calculation may be based on either the rate of temperature rise or the final equilibrium temperature of the gas. Both tuned and untuned resonators have been used successfully for both 3 and 1 centimeter band gas loads in high power measurement. For absolute measurements the meter is calibrated against a water load calorimeter.

Another adaptation of the calorimetric method is an indirect power measuring device utilizing a thermometer whose thermal element has been surrounded by an r-f power absorbing material; the dial or scale is calibrated to read in power units by comparison with the usual calorimeter standard. Zero power level is indicated at the ambient temperature of calibration, usually 25° C. One form of this device, suitable for field use use only, is made from a seven-eighths inch coaxial dry load and a Weston all-metal thermometer for measurement in the 10 centimeter region.

All the techniques described previously require complete absorption of the power incident upon the load or termination. There is another high level power measuring device, the Johnson Meter, which while determining power by the change in temperature requires only 1 percent of the incident power. A small section of wave guide wall or the outer conductor of a coaxial line is replaced by a section of high resistance material; the power dissipated in this material is sufficient to cause large temperature changes which are proportional to the transmission line power. A platinum resistance thermometer is wound on the high resistance material and another is wound about the wave guide or coaxial line. These 2 windings serve as 2 adjacent arms of a d-c bridge; to within a few percent, the bridge galvanometer current is directly proportional to input power. A standard calorimeter is used for calibration of this instrument. Since it takes such a small percentage of the main line power, the device may be classified as a power monitor.

2. "Hot Wire" Techniques.

A wattmeter which uses some form of a hot wire for its power detector achieves the measurement of the power by determination in some manner of a change in the electrical or physical characteristics of the hot wire.

Perhaps the oldest form of hot wire wattmeter is one using a load lamp similar to the incandescent lamp, useful for high power measurement at the lower microwave frequencies. If the power is dissipated in a suitable lamp, the lamp's brightness may be compared visually or by means of photocells with that of a similar lamp fed from a low frequency source. When the brightness of the 2 lamps is the same, it is assumed that their power inputs are then equal. In common with all other wattmeter types, the lamp impedance must match that of the line. The filament temperature coefficient of resistance should be as small as possible to minimize variations of impedance with power level; for general work a carbon filament lamp is most suitable, although tungsten is more easily worked and more commonly found in the latest types. A lamp having a filament of the simplest geometrical form and of the shortest length should be used at the higher frequencies in order to reduce variations of brightness along the filament as a result of the presence of a standing wave. This latter consideration quite obviously limits the power handling capability of a load lamp, except at the longer wavelengths, because of the objectionable physical size of a design which can dissipate several watts for a long period of time. Extreme care must be taken to shield the lamp so as to keep to a low value radiation losses due to length of dissipative element. Instead of comparing 2 lamps in making a measurement, only one can be used with a photocell or optical pyrometer which measures the brilliance of the filament. Taking into account the r-f losses in glass seals and metal contacts and change in resistance because lamp wires are larger in radius than the skin depth of the microwave current, the photocell or pyrometer-lamp combination may be calibrated by dissipating known low frequency power in the lamp. The lamps also may form 1 resistance arm in a bridge circuit, the operation of which will be described more in detail in Chapter III where the barretter is used. Lamp sensitivity is increased by evacuation of the envelope, but maximum safe power dissipation is attained by filling the lamp with some gas such as hydrogen. Load lamps have been manufactured in various special forms as terminations for coaxial lines. Due to the physical nature of the lamps and holders, the lamps must be provided with tuning elements for use at varying frequencies; there has been some success in designing broadband lamps, but it is believed that, at present, lamp techniques have given way to barretter or thermistor instruments in the low and medium level power measuring fields.

The immediate predecessors of the modern barreter were the 5 and 10 milliamp Littelfuses and Buss fuses, manufactured primarily for the protection of sensitive milliameters and other delicate equipment. The fuse was placed in one arm of a Wheatstone bridge; the resistance of the platinum wire being a function of the power dissipated in it, bridge unbalance would also be a function of power. Although the fuses were used with some success, it was quickly realized that their construction was inherently bad from a number of viewpoints. The tiny resistance wire being placed at right angles to the fuse axis produces a high reactance component of fuse impedance; the VSWR of such an element in either a wave guide or coaxial line mount is so high that impedance matching is at best a painstaking and extremely frequency sensitive operation. At wave lengths shorter than 10 centimeters the glass mounting for these fuses begin to absorb power and considerable measurement errors result. When removed from the envelope or when used for longer wave lengths only, the fuses proved to be fairly satisfactory, however.

The thermocouple, originally used in the measurement of r-f currents, has begun to gain some prominence in the microwave power measurements field. Its greatest advantage is that only a millivoltmeter is required; this is in contrast to the regulated power supply and numerous bridge components required by the thermistor or barretter. A principle disadvantage is that the thermocouple must be used within a small fraction of its safe power range. The millivoltmeter calibration is decidedly non-linear when use is extended over a wide power range. At high temperatures corresponding to high power levels equilibrium temperature is attained by cooling by radiation which is far more effective than conduction or convection cooling at low temperatures. The equilibrium temperature, thus, is not directly proportional to power. The thermocouple may be considered to be a generator with an internal resistance varying with power level. The internal drop and the terminal voltage, therefore, are not linear functions of power. Thermocouple sensitivity, except in the case of evacuated capsules, does not compare to that of thermistor or barreter bridges. Small sized capsules, needed to measure energy at wave lengths less than 10 centimeters, are difficult of construction and, further, such factors as wire radius exceeding skin depth and low d-c resistance preventing broadbanding reduce the usefulness of the thermocouple. The Bell Telephone Laboratories have engaged in development of refined forms of the thermocouple to eliminate many of the disadvantages listed above, although operation at the higher frequencies is still limited. Increased resistance has been obtained by use of carbon bridge thermocouples (a length of fine carbon filament is suspended across a short gap between the thermocouple wires) and resistive-bead thermocouples (the two wires of the thermoelement terminate in a tiny glass bead coated with a thin metallic film).

A thermocouple dipole was developed for monitoring radar transmitter power at 10 centimeters. The dipole is effectively a half wave 10 centimeter antenna, the center of which is distorted into a long hairpin bend. A thin constantan wire arched across the center gap loads the dipole. The hot junction is formed by spot welding one end of a fine Chromel-P wire to the center of the constantan wire; the opposite end of the Chromel-P wire is tied to the top of a vertical support rod. The complete antenna and thermocouple unit is enclosed in an evacuated bulb; since the "Q" is approximately 10, the device is reasonably broadband. Power being extracted from free space by the dipole generates a voltage in the thermocouple which is an indication of the field strength at the antenna. Thus, this device may be used as a continuous output monitor when located at a fixed position relative to the radar antenna. The design and development of an accurately calibratible directional coupler, however, has lessened interest in the thermocouple dipole; the directional coupler is much more useful in that it may be introduced at any convenient point in the wave guide without measurably affecting the output.

Today, by far the most common and best known elements of the "hot wire" type are the thermistor and the barretter, the latter type coming first in development. While the thermistor and barreter differ widely in electrical and thermal characteristics, each has its advantages which preclude at present the complete abandoment of one in favor of the other. The barretter as developed by the Sperry Gyroscope Company will be discussed in Chapter III of this paper. The thermistor as used in microwave power measurement takes the form of a bead of semi-conducting material bridging a narrow gap, the carefully controlled spacing being determined by operating frequency and other considerations, between two parallel platinum-iridium wires, 0.001 inch in diameter. The bead has the negative power coefficient of resistance characteristic of the metallic oxides such as nickel and manganese oxide of which it may be composed. In order to decrease the resistance to a desired value determined by the operating requirements of broad banding the impedance match, maximum power sensitivity, etc., metallic copper is finely dispersed through the metallic oxide which is originally in powdered form. The compressed powders are heated to a temperature at which they sinter into a strong compact mass due to recrystallization of the powders. Sometimes, for use at the lower frequencies, the thermistor may be enclosed in a glass envelope. Since bridge circuits in which the thermistors are used are similar both in principle and design to those in which the barretter may be found, no discussion will be given here (see Chapter III). A disadvantage of the thermistor is that its temperature sensitivity is quite high, requiring adequate compensation in the bridge construction in order that the wattmeter operation need not be limited to a very narrow ambient temperature range and that the bridge-thermistor combination sensitivity remain more or less constant over a band of temperatures. The thermistor, like the barretter, is generally used for the detection of powers under 10 milliwatts; both elements are designed to dissipate all power reaching their mounts. Thus, the correct design of the thermistor mount becomes a major consideration; factors affecting this design are the same as for the barreter to be discussed later. Having a coefficient of resistance of about 15 ohms per milliwatt under typical operating conditions, the thermistor is more sensitive than the barretter. Since the thermal time constant and heat capacity of thermistors are relatively large, they are ideally applicable to the measurement of pulsed power and give consistently accurate results under all conditions of pulsed power operation. It is in this one respect that the thermistor is far superior to the barretter in power detection capability. Another desirable property of the thermistor is that it will withstand much greater overloads than will the platinum wire barretter; this has come to be known as the "self-fusing" property. The mount impedance becomes badly mismatched before the thermistor can be burned out (e.g., compare a burn-out resistance of 5 ohms to a normal operating resistance of 200 ohms); the generator then delivers less power, so that while the generator may be capable of delivering burn-out power to a matched load it will not necessarily burn out a thermistor bead. Because of the small difference between its operating and burn-out resistance levels, the barretter lacks this advantage.

The barretter excels in certain instances as to suitability and economy of use. No manufacturing process has been devised which gives consistant d-c or microwave impedance characteristics to the thermistor; this defect is particularly apparent at the higher frequencies -- at 3 centimeters, for instance, the holder must be retuned when elements are changed. The barretter may be manufactured in comparatively large quantities meeting certain rigid requirements as to bias power required for operating resistance, VSWR set up in the line when used as a termination, etc.. The thermistor at best can meet only the bias power requirements with a very much more complex manufacturing process.

3. Power Monitors.

It is of particular interest at times to be able to continously monitor the power being delivered to some other unit without extracting any appreciable portion of it. Of the types of wattmeters previously mentioned, only the Johnson Meter and the thermocouple dipole meet this requirement. If a small percentage of the "main line" power is sampled by some such device as the directional coupler, then low level power measurement devices may be used as high level power monitors; the absolute value of load power can be determined by careful determination of the amount of coupling, or the meter-coupler combination can be used for relative indications only.

There have been several attempts made to use neon tubes for high power measurements. A major difficulty encountered in all cases is in obtaining tubes of required characteristics in large quantities. One scheme measures with a photocell the intensity of glow of a glass capillary filled with neon, inserted parallel to the wave guide axis into a slot in the wave guide; the glow intensity is dependent upon the line power level. In another, energy coupled by 2 probes spaced a quarter wave length apart is used to fire a pair of small bulbs; a single photocell views both bulbs. This arrangement presents troubles in the sensitive dependence of the coupling coefficient on probe depth. The British have experimented with a variation of this latter system which does not use a photocell; instead, variation in ionization current produced in lamps biased by constant voltage and exposed to an r-f field is used for power level indication. For a bias voltage less than the d-c "striking voltage", the resistance of the lamp may be as high as 0.1 megohm; this resistance decreases as microwave power is applied, causing an increase in current proportional to the power. A single microammeter gives the arithmetic mean response of the 2 lamps connected in parallel and may be calibrated against an absolute standard. Average power indications are obtained with these 3 schemes.

A special neon tube for magnetron bench testing consists of a 1 foot length of 0.5 mm. Pyrex tubing with a tungsten electrode sealed into the end and a gas reservoir at the other. The electrode conical tip protruding partially into the tube produces the "starting" potential gradient in the gas. The physical length of the gaseous discharge column is determined by the pulse power since the pulse width is usually much greater than the ionization or deionization times of neon; thus, this wattmeter differs from all others in that it responds to the pulse power level. The tube extends a short way into the guide and is installed normal to a broad side of the wave guide. Impedance matching is achieved by variation in tube depth and by use of an adjustable wave guide short. To study the magnetron stability of output, the length of the discharge column for each individual pulse may be observed by means of a rotating mirror.

To a limited extent, crystals have been used as rough indicators of low r-f power. Direct measurements may be made with uranium oxide crystals used as resistors in one arm of a bridge in the same manner as are barretters. A greater use by far, however, has been made of the rectifier property of crystals of such substances as silicon or germanium. Crystals, due to their applications in other fields, are readily available and, like thermocouples, they offer the advantage of an extremely simple indicator circuit, a microammeter; crystal cartridges can be made small enough for easy installation in the smallest sized transmission lines. These advantages of crystals are far outweighed by the disadvantages associated with their use. The fact that crystal power monitors must be calibrated against an absolute standard is not of itself a disadvantage; the calibration is not, however, permanent and may change appreciably due to vibration, shock or overload. Because the impedance of a given crystal is sensitive to power level and because of wide variation in characteristics among crystals, broadband impedance matching is difficult to achieve. Rectification sensitivity may vary by as much as 10 to 1 between crystals and is extremely temperature sensitive.

Vacuum tube "lighthouse" diodes show more promise than crystals in microwave use, because their calibrations are more stable and less temperature dependent and they can withstand greater overloads. In addition, the diode may be used over the extremely large power range of from 20 milliwatts to several hundred watts. The diode is usually mounted in a tunable cavity; the voltage drop across a load resistor may be calibrated as a function of the input power. The lack of popularity of the cavity mounted diode may be explained by the fact that changes in cavity coupling and internal losses make the calibration a function of frequency, cathode emissivity varies considerably among tubes, cavity construction is difficult and expensive and the tuning procedure is complicated.

A calibrated standing wave detector may be used to monitor r-f power; the measurement depends upon the determination of the electric field factors in a rigid transmission line. A short wire probe projects through a slot in the outer conductor, and is moved mechanically back and forth along the line over a distance of at least one-half wave length. Current in the probe is rectified by a crystal or applied to a thermocouple, and the resulting d-c is indicated on a microammeter. A simple formula involving a calibration constant and the meter readings determines the r-f power. A fundamental disadvantage, of course, is that two readings must be taken and then the power calculated.

III. THE BARRETTER

For the measurement of small powers, such as are available at the output of microwave signal generators, calorimetric wattmeters and the early load lamps which depended upon light indications are neither convenient nor sensitive enough. The slight water temperature rise due to low level power absorption in the calorimeter is simply not detectable. The lamp may still be used, however, if use is made of a property other than its light output which gives increased sensitivity and accuracy of measurement of low level power. When power is dissipated in a lamp, the filament temperature rises until a balance is obtained between radiation and conduction losses and the power input; this temperature rise causes and is accompanied by a change in filament resistance. Circuits may be arranged which can detect accurately a small change in the resistance, obtaining thus an indication of power well below the level required for lamp incandescence. Figure I shows the increase in sensitivity obtainable with a typical early load lamp. This is not a newly discovered property of the lamp; long before the development of the thermopile, it was used to measure heat radiation. The name bolometer, from the Greek "ray-meter", was derived from this use. One of the earlier uses of the bolometer, before being superseded by the thermocouple, was in measuring r-f currents; Tissot described this technique in 1904.

The bolometer which forms the heart of the present day wattmeter is usually a small bead of resistive material, such as the thermistor, or a short length of fine wire. Some forms of the bolometer have been discussed in the preceding chapter; in this chapter, a more comprehensive study of the characteristics and uses of the barretter, a special form of "hot wire" bolometer element designed expressly for microwave power measurement, is made. Variations in the characteristics of Littelfuses and load lamps, which are not objectionable in their normal use or at much lower frequencies, are not acceptable when consistently accurate results are desired; barretters were developed to meet these needs in the microwave region. While the thermistor, a later development still, has greater sensitivity, will withstand much greater overloads, and is more applicable to the measurement of pulsed power than the barretter, the barretter retains certain advantages which make it extremely useful. Due to its short thermal time constant, it can be used for audio demodulation. In c-w measurement, it is desired over the thermistor because (1) the resistance versus power relationship is more uniform among various elements, (2) it is less susceptible to ambient temperature changes, (3) the r-f holders are more easily designed and manufactured and (4) calibration is not required for each element because of uniformity of construction.

1. Equivalence of D-C and R-F Power.

In using the barretter to measure r-f powers, the assumption is usually made that the resistance of the filament is a unique function of the power dissipated in it independent of whether the power if r-f or d-c. E. Feenberg* has shown that the above relationship holds for powers of all frequencies with only a very small degree of error as r-f frequency is increased, if the wire radius does not exceed the skin depth. A brief review of his reasoning will be given here.

For a wire heated by direct current the temperature on the axis of the wire must be greater than at the surface. On the other hand, where r-f of sufficiently high frequency to give a pronounced skin effect is used, the heat production is confined to a thin surface cross section of the wire. Consider a wire of length "l", radius "a" and conductivity "$\theta(T)$". Let the absolute surface temperature required to dissipate the power "P" be "T_a".

In the case of pure skin effect (where the radius is less than the skin depth) with uniform temperature over the cross section, the resistance due to r-f heating alone is given by

$$R_a = \frac{\ell}{\pi a^2 \theta(T_a)}.$$

*Feenberg, E. (4)

This relation disregards variations in the r-f current along the wire, which are negligible if wire length is maintained short enough.

For a d-c heated wire, the temperature is a function of the distance "r" from the wire center and the resistance may be determined by

$$\frac{1}{R} = \frac{2\pi}{\ell} \int_0^a \theta(T)\, r\, dr \, .$$

Since "$\theta(T)$" varies inversely as the absolute temperature, for small variations in "T", it can be written

$$\theta(T) \cong \theta(T_a) - \frac{\theta(T_a)}{T}(T - T_a) \, .$$

After suitable algebraic manipulation of the above formulae the following relationship is obtained:

$$\frac{R - R_a}{R_a} = \frac{2}{a^2} \int_0^a \frac{T - T_a}{T_a}\, r\, dr \, .$$

The function "T(r)" can be determined by solving the heat equation in cylindrical coordinates:

$$\frac{k}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) = -p \cong -\frac{PJ}{\pi a^2 \ell}$$

where "k" is the thermal conductivity in calories/°Csec.cm., "p" the heat production in cal./sec.cm^3., "P" the total power in watts and "J" the conversion factor from Joules to calories (J=0.239 calories/Joule).

The solution of the heat equation is

$$T-T_a = -\frac{PJ}{4\pi a^2 \ell k}(r^2-a^2).$$

Substitution of this into the resistance relationship gives

$$\frac{R-R_a}{R_a} \cong 0.010\,\frac{P}{\ell T_a k}.$$

From this result it must be clear that even in the most extreme case "R" differs from "R_a" by a negligible amount, and the assumption of the equivalence of heating effect of d-c and r-f power must hold. Continuing along similar lines Dr. Feenberg shows that the total d-c resistance of the wire is a unique function of the additional power, independent of whether that power is r-f or d-c. Considering the two limiting cases where heating is entirely due to d-c or entirely due to r-f, he finds that the ratio of r-f to d-c resistance cannot differ from unity by an appreciable amount.

Some of the heat generated by power dissipation in the element is lost by conduction through the conductors which support the filament and make electrical connection with it; this heat loss reduces the resistance change in the element. Dr. Feenberg*has also shown that the end correction is so small, however, that any dependence of

*Feenberg,E (4)

the correction on the frequency of the dissipated power can be disregarded.

The above proof is the underlying principle of all barretter and associated biasing network design. To summarise, for a given barretter under conditions of constant ambient temperature and constant resistance:

(1). The input power may be d-c, a-c, r-f or microwave.

(2). D-c power and any higher frequency power may be applied simultaneously.

(3). Two or more different components, with or without d-c, may be applied simultaneously, limited by practical interaction effects (the barretter is an audio detector!).

(4). The sum of all power components must equal the required amount of any single component applied alone.

(5). The algebraic sum of changes in power components must be zero.

(6). Equal substitution of one or more components in any combination may be made for one or more components in any combination.

2. Barretter Design Considerations.

A wattmeter utilizing a barretter as the power detecting agent does not exist as an integral unit but rather as an assembly of selected components designed to work together. These components are:

(1). The barretter, the energy absorbing element.

(2). The barretter mount, an r-f head serving to couple the barretter to the r-f transmission line.

(3). The wattmeter bridge, a calibrated indicator of power changes in the barretter.

(4). The attenuator, in the form of a directional coupler or dissipative pad, necessary for measurement of power in excess of 10 milliwatts.

It is obvious that considerations of range, accuracy, reliability, sensitivity, and convenience in microwave power measurement cannot be confined to one component to the exclusion of the others. In this paper, a discussion of barretter and mount design considerations will be given in detail; factors affecting other components will be pointed out as they appear in relation to design of these components.

Design of a barretter for power measurement must take into account a number of inter-related, and often conflicting, factors. Some of these are:

(1). Wave guide or coaxial transmission line.

(2). Frequency or band of frequencies of operation.

(3). Resistance required for good impedance match in the mount.

(4). Cold wire resistance.

(5). Initial power level and overload power margin,

(6). Sensitivity desired.

(7). Configuration of element.

(8). Thermal and electrical characteristics.

(9). Expected or desired operating life.

(10). Physical strength.

(11). Resistance to fungus and moisture.

(12). Materials available.

(13). Ease and cost of manufacture.

In order for the power indications to have any significance whatsoever, it is essential that all r-f power reaching the barretter mount be converted into heat in the responsive element only. This requires that all diversion of power by reflection, leakage, and conversion elsewhere in the termination be held to an absolute minimum. Minimum power reflection is achieved by matching the impedance of the barretter and mount combination to the characteristic impedance of the transmission line. For broadband operation, the mount must be tunable over the range or its microwave impedance with the barretter in place must remain relatively constant over the band so that the VSWR remains at or below an acceptable maximum value. This problem of impedance matching involves a critical dependency of the electro-magnetic properties on the mechanical geometry of both barretter and mount. This is quite apparent when one considers the design of a fixed tuned broad band mount as will be discussed later. In this particular case, the insert tips projecting into the wave guide act in the same manner as a pair of tuning stubs.

Leakage and extraneous conversion losses must be eliminated primarily by proper holder design. Perhaps the greatest single source of leakage is in the low frequency connection to the ungrounded end of the barretter; use of a wave trap and condenser filter, if properly designed, eliminates most of this leakage. Each point of extraneous power conversion may be considered to be another resistive component; these losses thus not only reduce the power readhing the barretter by actual power consumption but further reduce the power because of the change in VSWR due to impedance mismatch.

As has been noted, the design of the barretter and mount should be coordinated to obtain the best impedance match to the transmission line. Since the barretter resistance is an integral part of the composite impedance, one would think that it could be arbitrarily determined from the above considerations. The barretter resistance, however, is dependent upon the material used in its manufacture; since the physical size and shape of the resistive element are limited by electro-magnetic considerations, the ultimate resistance reached in design is a compromise value.

A wire stretched across a wave guide or a short length (less than a quarter wave length) of shorted coaxial cable acts as an inductive reactance; the barretter in its use fits these cases exactly. In order to keep its reactance low, it is necessary that the responsive element be made short in comparison to one wave length; the usual standard is that it shall be shorter than one-tenth wave length.

In order that the r-f and d-c currents shall encounter equal resistance or cross section in the wire, the wire size should be made small enough that skin effect is insignificant; this condition obtains when wire radius is less than the skin depth which is a function of frequency. Wire radius of the barretter designed for broad band use must, therefore, satisfy this condition at the highest expected frequency.

A platinum wire which gives the desired resistance characteristics for the length and radius permissible is known as Wollaston wire, named for the Wollaston process of drawing fine wire and an enclosing jacket of silver simultaneously. This wire is commercially available in platinum core diameters beginning at 0.000013 inch; because of difficulties of measurement of such small diameters, the wire is specified in terms of its resistivity in ohms per foot at 25°C. The platinum core can be seen with the naked eye only under intense illumination and is too fragile to handle when working with a magnifying lens; the silver coating about 0.002 inch in diameter makes the wire much easier to mount and handle. The silver is etched away with an acid solution until the desired resistance and sensitivity is reached.

The thermal characteristics of the barretter like its impedance are determined by its size, shape, and material. The characteristics of the finished barretter must be determined with the element in its mount since the mount, by acting as a thermal sink, affects the overall performance.

The thermal time constant of the power detecting element must be as long as possible and is determined by its configuration and material of which it is composed. A long thermal time constant is desired in order to prevent too close "following" of a varying power level as occurs with pulsed power whereby measurement errors are introduced; the thermistor possesses a great advantage over the barretter in this respect. The speed with which the barretter follows power levels limits it to use at a lower than nominal average power level when measurements of modulated or pulsed power are being made; peaks of the modulation cycle quite easily could cause burnout or a permanent change of the barretter characteristics even though the average power were quite low.

The ability to detect small changes in total input power, i.e., the sensitivity of power measurement, depends upon

(1). Sensitivity of associated bridge and indicator.

(2). Ohms per milliwatt sensitivity of the barretter.

(3). Total initial or bias power. The smaller the increment is in relation to total bias power the easier it is to indicate the change.

Closely tied in with these factors is the sensitivity to ambient temperature changes. This latter sensitivity factor is also influenced by element and mount configuration. It has been determined that operation at higher temperatures reduces the sensitivity to temperature changes in the surroundings.

3. Construction of the Sperry Type 821 Barretter.

The Sperry Type 821 barretter, commonly referred to as the "200 ohm" unit, was specifically developed for use with the 3 centimeter Sperry Type 82 mount to be described later but is being used sucessfully in other mounts at various frequencies in both wave guide and coaxial line applications. The value of 200 ohms is an optimum value determined in the design of the broadband mount. This barretter is too large to be used at wave lengths of 1 centimeter or less, where it has been found necessary to use uncapsuled Wollaston wires.

The responsive element of the barretter is a fine platinum wire about 0.00006 inches in diameter. It is suspended in a hollow cylinder of dielectric material between metal inserts at the cylinder ends, as illustrated in figure II. Machined dimensions of all parts are held to close tolerances as required by electrical considerations. The dielectric material is G. E. 1421 copolymerstyrene. Conducting surfaces for r-f currents, exclusive of the platinum wire, are gold and silver. The small diameter platinum wire is obtained by etching away with nitric acid the silver from the platinum core of Wollaston wire. At all stages of production, care is exercised to keep all parts absolutely clean internally and externally; contamination not only adversely affects the impedance matching but also introduces power measurement error.

The technique for producing barretters in limited quantities were developed in both the Radiation Laboratory and at the Sperry Gyroscope Company during the war. By 1945 the Sperry Company was in a position to produce the 821 barretter in sizable quantities. The construction technique developed by the Company is described here.

The physical components of this barretter, shown in figure III, are the filament wire, the end inserts which support the filament, the cylindrical capsule with a wall section removed, and the wall section. Assembly is as follows:

Step (1). The metallic end inserts are heat sealed into the cylinder. A jig is used to control the heating, to properly space the inserts, and to prevent distortion of the cylinder during heating.

Step (2). The filament wire, cut to the proper length, is crimped with a special tool so that it has a slight sag. The wire does not resist tension greater than that caused by its own weight; the crimp thus allows for dimensional variation due to a change in ambient temperature, power level, etc.

Step (3). The filament ends are fitted into tiny holes drilled into the ends of the insert support leads and soldered into place. Care must be excercised to completely fill the support holes with solder and keep the solder from projecting beyond them, since the electro-magnetic characteristics may be changed appreciably by any soldering faults. This work is done under a microscope.

Step (4). A controlled drop of acid is applied through the opening in the cylinder to etch away the proper amount of silver. Aerosol is added to the aqueous solution of nitric acid to reduce the acid surface tension; this prevents breaking of the fine wire by surface tension forces when it is removed from contact with the acid solution. The drop of acid is smaller than the length of wire to be etched, so that it can be moved along the wire to the desired length. Etching is stopped when a special d-c bridge, of which the barretter is one arm, comes into balance. At this time, the resistance of the barretter, which depends on its average temperature and hence on the current, has then increased to the desired value at a predetermined current. The acid or its fumes must touch only the length of wire desired, as otherwise it may attack the solder and modify the characteristics as noted above.

Step (5). The unit is thoroughly washed to remove any acid residue and then dried; otherwise, silver nitrate crystals may form and break the wire.

Step (6). By the process of cementing the accurately fitting wall section into the aperture the barretter is made symmetrical and air and water tight.

Step (7). The barretter is tested in a mount to see that, with the designed bias power being dissipated in it, the impedance match is good; i.e., the VSWR is below a certain prescribed maximum. All barretters also must withstand an overload input power, 32.5 milliwatts, at 25°C without effect on initial bias power required or VSWR obtained.

4. The Type 82 Broadband Wave Guide Mount for the 821 Barretter.

The use of the Littelfuse in microwave power measurement declined primarily because it did not lend itself to broadband impedance matching in microwave mounts. The 821 barretter has both desirable and reproducible microwave impedance characteristics; as stated before, it was developed for use with the 3 centimeter type 82 wave guide mount which was the first in a series of broadband mounts designed by the Sperry Gyroscope Company.

The wave guide mounts in use before the development of the broadband mount usually had two tuning adjustments (one shorting the guide beyond the bolometer or Littelfuse and one shorting the short coaxial lead at the grounded end of the bolometer) on the holder to tune the impedance of the thermally sensitive element so that it presented a matched termination to the wave guide. Whenever the element had to be replaced, the holder had to be retuned. The first requirement then to be met in the use of a fixed tuned holder is that the barretter elements be interchangeable; the 821 barretter fully satisfies this requirement.

An 821 barretter was mounted in a tunable 3 centimeter wave quide mount. It was balanced sucessively at resistances of 125, 200, and 250 ohms with the holder being tuned in each instance to match the wave guide impedance at a wave length of 3.33 centimeters. Measurements were then made of the power SWR as frequency was varied. Results of these measurements are given in figure IV; the bandwidth is seen to increase with increasing resistance, but the wires would be operating dangerously close to burnout at 250 ohms. A suitable compromise between bandwidth and fuse protection placed the operating resistance for these barretters at 200 ohms.

The bandwidth with a matched termination alone, however, was not so great as was desired. After a trial and error process which eliminated many other schemes, a resonant window in the wave guide portion of the mount was resorted to as a means of increasing the bandwidth of the holder-barretter combination. A resonant window consists of a thin metal diaphragm perpendicular to the axis of the wave guide; a narrow slot parallel to the broad side of the guide is in the diaphragm. This window acts like a parallel resonant circuit shunting the transmission line. If its resonant frequency, "Q", and characteristic impedance are known, its behavior in the neighborhood of resonance can be completely predicted.

Resonance occurs when the slot length is approximately one half the free space wave length. The "Q" is in excess of several hundred, so high that losses may be neglected for this application. The characteristic impedance increases with slot width and decreases with increasing thickness of diaphragm.

The following reasoning and procedure were employed in making use of and locating the broadbanding window. With an average barretter biased to 200 ohms inserted, the holder was tuned to match the load at 3.2 centimeters. The wave length was varied and the mismatch noted. At 3.45 centimeters a power SWR of 2.3 was observed. While a simple inductive window would have corrected this SWR at this wave length, a mismatch would have been introduced at 3.2 centimeters, the wave length for which the holder was tuned. On the other hand, a window resonant at 3.2 centimeters placed anywhere in the guide would have no effect at this frequency on the wave guide characteristics. At 3.45 centimeters, however, it would introduce a shunting inductive susceptance, the magnitude of which could be varied by changing the characteristic impedance of the resonant window. The correct susceptance properly located along the guide then provided for a matched load at 3.45 centimeters but did not affect the match obtained at 3.2 centimeters. A typical curve of power SWR versus frequency obtained by this means is compared with that of simple tuned holder in figure V.

In the final design of the holder, the tunable shorts were replaced by fixed ones. The barretter at one end is grounded to the wave guide through a coaxial connection and at the other end is supplied with the biasing power through an r-f trap. This holder may be used over a 12 percent band of wave length from 3.13 to 3.53 centimeters. A number of barretters selected at random were tested in the holder over this band. The highest power SWR noted was 1.66, corresponding to less than 2 percent power reflected from the holder.

An assembly drawing of the first model is shown in figure VI. The wave guide portion of the holder has now been shortened so that the flange is located at the window, providing easier assembly and manufacture. Holders similar in design have been built to cover other frequency bands; the external shape has been much refined. Similar principles have been applied to the design of holders for use with coaxial transmission lines.

5. Characteristics and Ratings of the 821 Barretter.

Since the mount acts as a thermal sink and so affects the overall performance of the barretter, the characteristics of the barretter must be obtained while in a mount. The data following were obtained with the type 821 barretter operating in the type 82 broadband mount.

5.1. Current versus Resistance.

The power required for the barretter to reach 200 ohms in the mount averages 15.3 milliwatts at 25°C ambient temperature; the d-c current necessary to obtain this power is 8.75 milliamperes, a variation of ±0.25 milliamps being allowed in production. Figure VII shows characteristic curves of current versus resistance at ambient temperatures of -40, +25, and +70°C, for a representative barretter requiring 8.75 milliamps for 200 ohms at 25°C. Data was taken with the barretter as one arm of a precision d-c bridge. Thermocouples were used to measure temperatures adjacent to the barretter in the mount and external to the mount, successive temperature runs being made only after the two temperatures equalized.

5.2. Power versus Resistance.

The curves of power versus resistance in figure VIII were plotted from calculated values based on the curves in figure VII. A study of the curves leads to the conclusions that:

(1). The required power for a given resistance decreases with increasing ambient temperature.

(2). With fixed input power, the resistance increases as the ambient temperature increases.

(3). Normal sensitivity, i.e., the slope of the curve in terms of incremental ohms per milliwatt change in power, is greater at (a) low power levels for a given ambient temperature, (b) low temperatures for a given resistance or power level.

(4). Non-linearity signifies deviation from true "square law" response; this will be discussed more fully later.

5.3. Power versus Ambient Temperature.

This curve, figure IX, was derived from the data of figures VII and VIII. It shows that the power required for 200 ohms decreases very nearly linearly as the ambient temperature increases.

5.4. Sensitivity.

Barretter sensitivity must be qualified in actual practice according to the type of bias circuit used. Two factors cause a difference between "normal" sensitivity and "effective" sensitivity. The first reason is that an increment in barretter power results in an increment in resistance according to two successive points on the power versus resistance curve and not on the tangent at the initial point. Secondly, the effective sensitivity will exceed the normal sensitivity for a constant current d-c supply and will be less than normal for a constant voltage supply. When "E" is constant, the d-c power decreases as "R" increases because of addition of r-f power, providing for a net power increase less than the r-f power increment. A constant current supply tends to amplify excursions in barreter resistance, since the d-c power dissipated increases as "R" increases with r-f power. When a barretter is employed in a self-balancing bridge circuit, wherein a bias power component change automatically compensates for changes in microwave power, the speed at which the bridge can react is a factor in limiting the barretter resistance excursions. The effect varies with the type of modulation of the microwave power, being least for conditions approaching c-w.

Figure X shows the change in normal sensitivity with ambient temperature at 200 ohms initial resistance. This curve is based upon the average of the normal sensitivity derived from curves like figure VIII for a number of barretters selected at random. At 25°C, the average normal sensitivity was 4.464 ohms per milliwatt. There was a scatter of sensitivities noted which indicated that there was no correlation between the sensitivity and the power required for 200 ohms.

5.5. Square Law Response.

As has been noted before, the barretter power versus resistance curves show that the barretter does not conform strictly to square law behavior. The barretter, however, more closely approximates an ideal power detector than the thermistor or crystals in that its resistance change is very nearly directly proportional to the power dissipated in it. A study* of the static characteristics has shown that the following empirical formula holds true:

*Eberle, E.E. (3)

$$R_s - R_o = KP^n$$

where "R_s" equals average operating resistance when dissipating P watts; "R_o" equals cold resistance with zero power; "K" equals a constant; and "n" equals index of square law behavior (unity for perfect response; usually 0.9). The response is more nearly square law in the case of constant current circuits.

As in the case of sensitivity, there is a slight distinction between normal and effective response. The effective response of the barretter, the increment in resistance with an increment of r-f power, is always less than the normal response, the increment along the tangent to the power versus resistance curve at the initial bias point; this is assuming that there is no incidental change in d-c power level occasioned by the addition of r-f power. The percent discrepancy referred to initial bias conditions may be determined by a comparison of the two ratios of final initial resistances. Since the tangential or normal response ratio is equal to the power ratio, the percent deviation may be written

$$\delta = \left(\frac{R_2}{R_1} \cdot \frac{P_1}{P_2} - 1\right) \cdot 100$$

where "R_1" equals initial resistance due to bias power

"P_1", and "R_2" equals final resistance due to total final power "P_2".

A representative curve of incremental power versus deviation from square law response is shown in figure XI; the source of data was the 25° curve of figure VIII. It should be noted that the increase in sensitivity afforded by constant current bias will reduce the deviation; a higher bias power would also help.

5.6. Response versus Audio Frequency.

While there has been no absolute definition yet of the thermal time constant of the barretter, one method defined it in terms of the audio frequency response of the barretter. The time constant is defined as the reciprocal of the angular frequency at which the response is reduced to one half power. This frequency was discovered to be 1000 π radians per second. A bridge circuit affording essentially constant current d-c for the barretter was kept balanced for 200 ohms barretter resistance with one milliwatt of 20 percent sine wave modulated 10 megacycle r-f furnishing part of the bias. The sinusoidally varying voltage drop developed across the barretter was measured over the audio range from 100 cps to about 15 kcs using a wave analyzer to determine the fundamental and second harmonic response. The two curves in figure XII are expressed in decibels relative to the power in the fundamental at 100 cps. 100 cps was chosen as a minimum because at lower frequencies the physical expansions and contractions of the filament as it follows the power levels are sufficient to shake it in two. The second harmonic response is approximately 20 db down from the fundamental at 100 cps and falls still further below it as frequency is increased. The fundamental response itself at 8 kcs is 20 db down from the reference. This characteristic response of the barretter to audio rates of change of power such as occur in modulated or pulsed r-f emission explains why the thermistor is preferred for use in pulsed power measurements. It also shows why the measurement of modulated signals becomes more accurate as the frequency of modulation or pulsing is increased; the barretter follows the power level changes less closely and remains nearer the resistance which it would assume with the bias power plus average signal power.

5.7. Overload Ratings.

Compared to the power required for 200 ohms, the safe power overload is about 100 percent. The safe maximum power to be dissipated in the barretter varies inversely as the ambient temperature. This safe overload factor pertains to c-w power only; with pulsed or modulated power, the overload factor is much reduced because the barretter in attempting to respond to power peaks may burn out or change its characteristics considerably.

Changes in barretter characteristics at a sub-burn-out level are believed to be the result of an eutectic alloying of platinum and residual surface silver. Extreme care in the original etching operation is taken to avoid leaving traces of silver. Though the center of the wire be clean, the ends will always have some silver remaining. The temperature of the wire is a maximum in the middle due to end cooling effects; thus, the alloying temperature is reached progressively from the center outward towards the ends of the wire under overload conditions. When the hottest spot begins to emit visible red light, alloying begins; in normal use, however, the wire never reaches incandescence. This alloying can be controlled and can increase the average cold resistivity by as much as 25 percent. If the original alloying temperature is not again exceeded, the new characteristics will be stable; in addition to the change in cold resistance, sensitivity increases slightly and the required power for a given resistance is reduced.

5.8. Mechanical and Electrical Ruggedness.

The barretter is inherently waterproof, its characteristics not changing even after immersion for 24 hours in fresh water. Drop tests show that the barretter in its mount may be dropped as much as 4 feet onto a steel plate with no change in electrical or physical characteristics. Vibration and shock do not seem to effect any changes either. The type 821 barretter seems to be extremely rugged mechanically.

Barretters have been biased to 200 ohms in a life test of over 10,000 hours and have given no sign of changing characteristics or imminent failure.

6. Power Indicating Circuits for Use with the Barretter.

When additional power in the form of microwave energy is dissipated in a barretter, there is a corresponding change in the resistance of the element. It is this change in resistance which must be detected and indicated on a suitably calibrated meter in the wattmeter employing the barretter. No matter what form the power indicating circuit may take, it not only must detect the resistance change but also must furnish an initial biasing power for the barretter.

Perhaps the simplest and most elementary form of circuit to accomplish this dual purpose consists of a barretter which receives its bias power from a battery (in series with a high resistance) and a d-c voltmeter to measure the voltage across the barretter. The series high resistance insures that the resistance variations in the power detector will not affect the d-c current. R-f power in the barretter increases its resistance and thereby the d-c voltage drop; with a properly calibrated voltmeter, the r-f power may be read directly. This scheme provides very rough measurements only and is subject to many possible errors due to change in ambient temperature, etc.

The barretter resistance monitoring network or wattmeter most generally takes the form of a low frequency bridge, in which the barretter is one arm. A number of different bridge circuits are in common use, and different circuits offer advantages in accuracy, ease of operation or temperature sensitivity. For crude measurements, the degree of unbalance of the bridge when r-f power is impressed may be used to give direct readings of r-f power; the galvanometer across the neutral arms of the bridge must be calibrated. Again, the calibration is a function of the ambient temperature and large errors are possible. An advantage, extremely helpful in field use, is the speed with which measurements may be made.

A more fundamental approach to the problem is that of accurately measuring the barretter resistance in a bridge network with and without r-f power impressed. Referring to the power versus resistance curves, the change in power necessary to obtain the observed resistance change is equal to the r-f power applied. This technique is limited to measurement of powers above a milliwatt as the cold resistance of the detector is a function of ambient temperature and calibration is not reliable unless this is accurately controlled.

Another rather basic technique is one in which the bridge is balanced by varying the d-c bias power first with the r-f applied and second with the r-f removed. The d-c power in the barretter in each case may be computed from the amount of the bias current and the bridge resistances. The difference in barretter d-c power is equivalent to the applied r-f power.

The 3 bridges just described use d-c power only for bias, but there are many other bridge designs which call for a combination of d-c and a-f biasing power. Some use d-c and a-f to establish the initial balance and then vary one or the other for rebalancing after r-f is applied. In the self balancing bridge, both are used for bias but usually only the a-f is varied for rebalance. Two direct reading bridges, one a self balancing type, will be described to illustrate the use of 2 different low frequency biasing powers. Both are Sperry Gyroscope Company applications of this type of design.

A manually balanced direct reading bridge, Sperry type 84-B, is shown schematically in figure XIII. The milliameter in the barretter arm is calibrated non-linearly to read from 0 to 10 milliwatts of r-f power. Self-calibration is achieved by use of a precision resistor equal in value to the bridge balance barretter resistance and which initially is substituted for the barretter. The d-c current is adjusted until the milliameter reads 0 r-f power (10 milliwatts d-c). Then, with the barretter in the circuit, the 100 kcs power is adjusted until the galvanometer indicates zero unbalance; i.e., 10 milliwatts d-c plus 100 kcs power biases the barretter at 200 ohms. After introduction of r-f power, the bridge is rebalanced by varying the d-c, and the r-f power is read on the milliammeter. Accuracy of results, better than ±10 percent, requires the use of precision resistors throughout the bridge as well as accurate meter calibration. There is no need for sensitivity compensation because of the self-calibrating feature; drift errors are insignificant because of inherently low bridge sensitivity. This bridge is particularly well suited for field use due to its simple compact design and accuracy.

In the Sperry type 123-A Wattmeter Bridge, a more advanced type, the bridge is kept in a near balanced condition at all times by incorporating it in the feedback circuit of an oscillator. The required bias power for the 821 barretter is obtained from a combination of d-c and 10 kcs power. The 10 kcs power supplied by an amplifier-oscillator exceeds by about 6 percent the full scale r-f power reading (10, 1 or 0.1 milliwatt); d-c power makes up the remainder of the bias required for bridge balance. A schematic arrangement of the bridge is shown in figure XIV. The bridge is connected so that there is positive feedback to the amplifier (A) when the barretter (B) resistance is lower than resistance (R) needed for bridge balance. If r-f power is applied to the barretter, its resistance increases and negative feedback results in (A) supplying less 10 kcs power; the bridge is so designed that the r-f displaces an equal amount of 10 kcs power in the barretter. The vacuum tube voltmeter across the oscillator output thus may be calibrated to read r-f power directly, since this output is inversely proportional to the r-f power. The original zero-setting operation is the only adjustment required in order to obtain a reading; zero-setting consists of varying the d-c bias and, through the change in feedback, the 10 kcs power until the vacuum tube voltmeter scale reads 0 r-f power (indicating full scale value of 10 kcs output). This zero setting makes the necessary corrections for barretter differences within the manufacturing tolerances and ambient temperature variations. Microwave power measurements made with this bridge-barretter combination have an accuracy of better than ± 5 percent.

7. Accuracy of Power Measurement; Errors Encountered in Bolometric Wattmeters.

A question that comes readily to mind is whether microwave wattmeters are actually measuring power or just something proportional to power. At present the calorimeter is the generally accepted absolute standard of power measurement against which comparisons may be made, although considerable care is required to reduce calorimeter errors due to improper design or use below 2 or 3 percent. It is usually necessary to compare the results of 2 or 3 instruments and, from the results, make a judicious estimate of the errors involved in each measurement. This technique may also be followed to measure the relative error as a function of some variable when only 1 of the instruments is subject to error from the variable conditions.

The question of the equivalence of the heating effect in the barretter of d-c and r-f power has already been discussed. If the filament length becomes an appreciable portion of a wavelength at the higher frequencies, a standing wave may form along the filament. It has been shown theoretically that serious errors can result from nonuniform current distribution when the power-resistance relation of the bolometer is not linear and when the power being measured is a considerable part of the total power dissipated in the barretter. For short filaments, the error will be large if the filament is at or near a current node. The magnitude of the error increases dharply with increasing power level for a given bolometer.

Many barretter designs utilize a glass envelope to protect the wire and provide a mechanical support. No measurable r-f losses are found at 10 centimeters, but appreciable losses occur in the glass at 3 centimeter and shorter wave lengths. At these shorter wave lengths wires are either enclosed in low loss dielectric material (such as copolymerstyrene in the case of the 821 barretter) or supported by the mount and left exposed entirely.

Errors may also arise with the short time constant barretter in certain bridge circuits if the input signal is amplitude modulated or pulsed at a frequency sufficiently low for the barretter resistance to vary over the course of a modulation cycle. Generally speaking, the greater the cyclic deviation of barretter resistance from the value corresponding to true average power the greater will be the resulting error. Such deviation is minimized at high repetition rates, low peak power and low average power in pulse applications, and at high frequencies and low percentage of modulation in modulated c-w applications.

A theoretical study by O. Lundstrom* has shown that

* Lundstrom, O.C. (9)

measurements of power modulated or pulsed at low frequency should have the greatest error when equal arm d-c bridges are used, power indications dropping to 50 percent of actual power at the higher levels; unequal arm or constant current d-c bridges read about 90 percent of actual around 15 milliwatts; self-balancing bridges should give good readings until the peak power exceeds wattmeter full scale reading after which time the wattmeter readings remain constant no matter how much the r-f power may be increased. An opposing theory, at least in the case of the equal arm bridge, is advanced by T. Moreno* who believes that measurements would be in error by only a few percent at the most. To date there has been no data published which would bear out or refute completely either theory.

The author, in checking the measuring capabilities under pulsed power conditions of the 123-A bridge described previously, found that the bridge could measure the power quite accurately if the operating conditions were favorable. But the power indications could not always be trusted, because there was apparently some interaction or cross modulation effect of the pulse frequency and the bridge 10 kcs signal which produced highly improper action in the feedback and oscillator networks; the frequencies at which these occurred were a function of the barretter characteristics and did not appear to depend upon pulse length or duty cycle. The readings under these conditions of poor operation were sometime high, sometimes zero, and

*Moreno, T. (13)

sometimes too low; the reactions could not always be predicted, but it is believed that this reaction may occur in all types of self-balancing bridges employing an audio frequency oscillator as a variable bias source for the barretter.

Accuracy of power measurement depends not only upon use of the barretter under suitable conditions but upon the barretter and the mount together forming a good impedance match to the transmission line. An improper r-f termination, by setting up standing waves in the line, will prevent all the power incident to the mount from acting on the barretter. Improper mount design can locate the filament near a current node, causing low power readings. Sliding contacts in adjustable components of tunable mounts may be found to permit considerable r-f leakage in addition to altering the impedance match; use of capacitive by passes and quarter wave traps where necessary will eliminate a good percentage of the losses. In the microwave region the current no longer flows in or through a conductor but on its surface. To prevent power losses in transmission lines, therefore, it is necessary to provide good conducting surfaces. Microwave reflections will be produced by any surface discontinuities or obstructions. For these reasons, it is the practice to silver plate interior metal surfaces of all holders and measurements lines and to take particular care in their design.

In instruments providing a fixed bias for the barretter, error due to impedance mismatch may occur when the ambient temperature is not that specified in the design; the total input power required to obtain the initial barretter resistance decreases as the ambient temperature increases. Sensitivity increases somewhat with decreasing temperature and at the same time decreases slightly due to higher power levels.

Power measurements made using a balanced bridge and by the substitution method may be considered free of errors resulting from changes in barretter sensitivity, provided the minimum sensitivity at high ambient temperatures is adequate to obtain sufficiently accurate balance. At relatively high r-f power levels, when most of the initial low-frequency biasing power has been replaced by the r-f power, the bridge low-frequency supply voltage is near its minimum and the overall bridge sensitivity is proportionately reduced, placing a limit on the accuracy obtainable.

Unbalanced bridge power measurements made at any but the calibration ambient temperature are subject to the following kinds of errors if uncompensated:

(1). Calibration error, due to different bridge sensitivity and different supply voltage at the new temperature.

(2). Calibration error, due to different barretter sensitivity at the new temperature; sensitivity changes nearly one percent per degree centigrade near 25°C.

(3). Calibration error, due to change in galvanometer sensitivity; galvanometer resistance varies with temperature.

(4). Calibration error, due to temperature sensitive bridge components.

The preceding errors apply if the temperature is constant though not the calibration temperature. Should the temperature change after the initial balancing adjustment, an additional zero drift error will result from the change in initial barretter power requirements.

Compensation circuits may be added to both balanced and unbalanced types of bridges to reduce errors arising from ambient temperature differences and variations. This compensation is not needed in those bridge circuits which incorporate a self-calibration feature, as has already been noted.

The unbalanced bridge is subject to additional error from r-f impedance mismatch since the barretter resistance increases as r-f power is added. The measurable power is limited usually by the tolerable degree of mismatch; otherwise, it depends on the difference between the initial and safe maximum power levels.

When directional couplers or dissipative attenuators are used to determine high level power, the calibration accuracy of these devices directly affects the overall accuracy of the measurement. Calibration errors are a function of the ambient temperature, the frequency of operation, and the power level to varying extents dependent upon the type of power step-down device, and may become quite serious.

8. Conclusions.

The power measuring technique which may be used in any one application is dependent primarily upon whether absolute or relative measurements are to be made. The next most important factor is the power level being measured. Other factors such as accuracy of measurement, type of transmission (e.g., pulsed or c-w), transmission line used, etc., affect the choice of method.

The water load calorimeter is used as a standard for calibration of all other types of meters, but must be used at power levels above a few watts in order to achieve the desired accuracy. Thermistor-bridge combinations, if accurately calibrated, provide a consistant sub-standard for low level powers of all types of transmission. Barretter-bridge combination can be used as a sub-standard at low level c-w powers only, again with the requirements of accurate calibration.

The field of microwave power measurements is open for extensive development of new types and improvement of existing meters. The frequencies being used are gradually approaching the infra-red range, a fact which is introducing new considerations and problems in meter design.

BIBLIOGRAPHY

1. Clayton, R.J., J.E. Houldin, H.R.L. LaMont, and W.E. Willshaw. Radio measurements in the decimetre and centimetre wavebands. Institution of electrical engineers, Journal. Part III 93:97-116, March 1946.

2. Early, H.C. Wideband wattmeter for wave guide. Institute of radio engineers, Proceedings. 34:803-807, October 1946.

3. Eberle, E.E. The Sperry type 821 barretter for microwave measurement and detection. Sperry report 5224-1042, July 24, 1945.

4. Feenberg, E. Frequency dependence of power-resistance relation in hot wire wattmeters. Sperry report 5220-108, March 10, 1943.

5. Feenberg, E., and R. Kahal. Apparent r-f power as a function of filament length and nodal position in a hot wire wattmeter. Sperry report 5224-1031, April 23, 1945.

6. Gaffney, F.J. Microwave measurements and test equipments. Institute of radio engineers, Proceedings. 34:775-793, October 1946.

7. Hickin, E.M. Bolometers for VHF power measurement. Wireless engineer. 23:308-313, November 1946.

8. Jones, W.T. Microwave test and measuring equipment. Electronic industries. 5:48 , November 1946.

9. Lundstrom, O.C. Errors in bolometric measurement of pulsed radio-frequency power. Sperry report 5224-1062, June 14, 1946.

10. Montgomery, C.G. Technique of microwave measurements. New York, McGraw-Hill, 1947. (Massachusetts Institute of Technology. Radiation laboratory series. No. 11)

11. Moreno, T. Microwave transmission design data. Great Neck, New York, Sperry Gyroscope Company, 1944. (Sperry publication 23-80)

12. Moreno, T. Fixed tuned broadband wattmeter using a broadbanding window. Sperry report 5224-1003, June 19, 1944.

13. Moreno, T. Errors in bolometer measurement of pulsed radar signals. Sperry technical memorandum 4, August 15, 1946.

14. Moreno, T. and O.C. Lundstrom. Microwave power measurement. Institute of radio engineers, Proceedings. 35:514-518, May 1947.

15. Peskin, E. and E. Weber. D-c thermal characteristics of microwave bolometers. Review scientific instruments. 19:188-195, March 1948.

16. Rambo, W.R. Coaxial load for ultra-high-frequency calorimeter wattmeter. Institute of radio engineers, Proceedings. 35:827-829, August 1947.

17. Schneeberger, R.J. Neon tube power indicator. Westinghouse research report SR-156, December 1, 1942.

18. Shaw, R.C. and R.J. Kircher. Coaxial type water load and associated power measuring apparatus. Institute of radio engineers, Prodeedings. 35:84-87, January 1947.

19. Webber, H.E. Power measurement in the microwave region. Sperry report 5220-109, March 9, 1943.

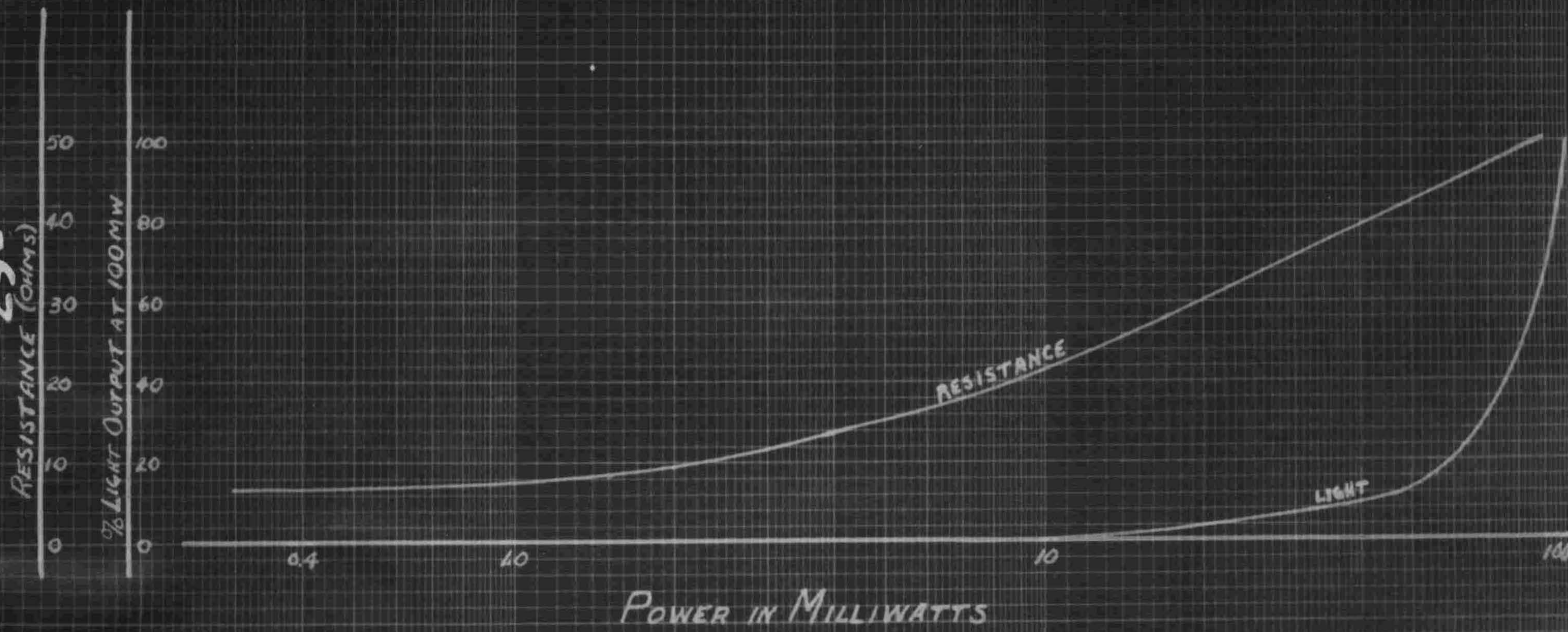
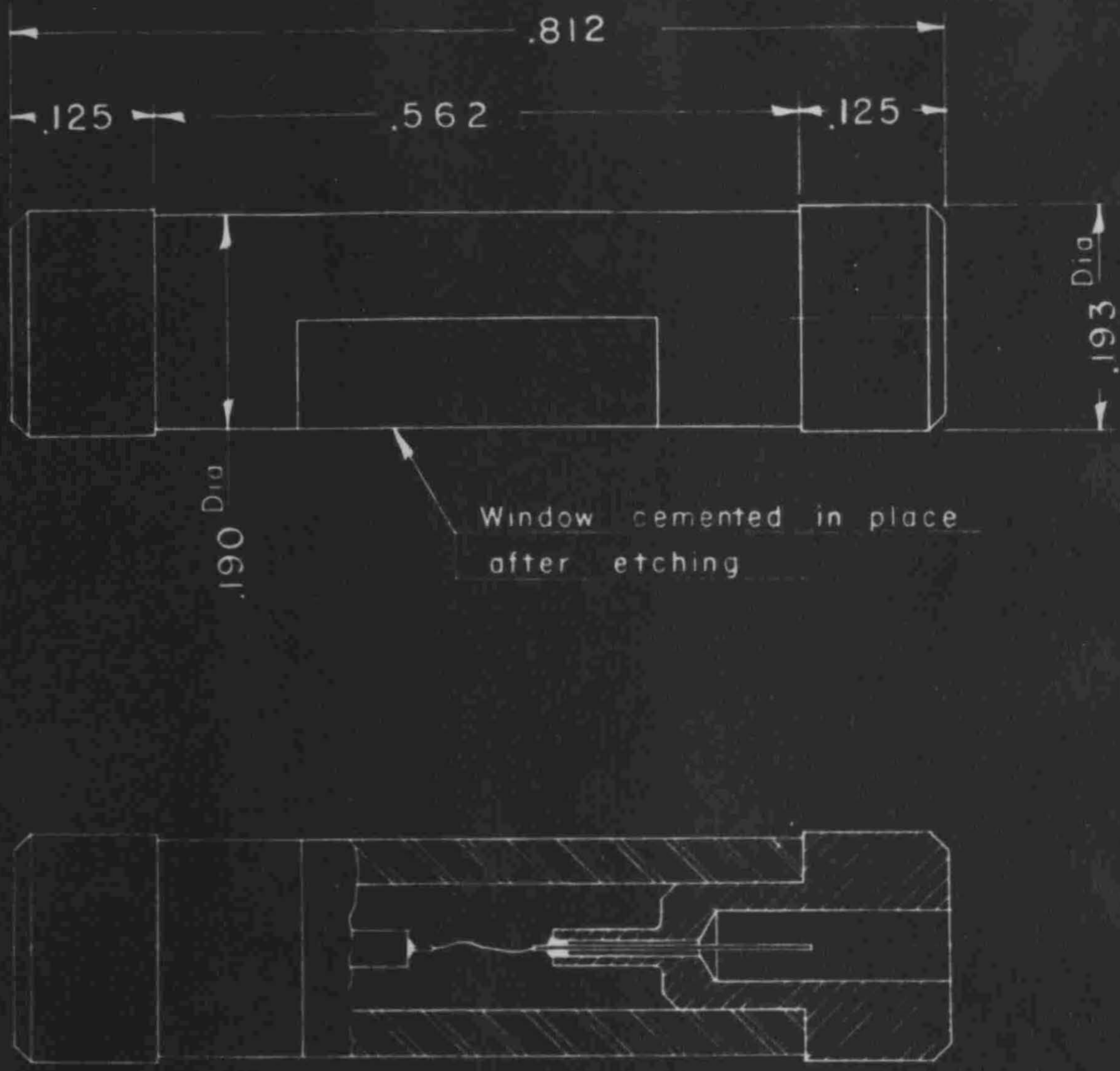


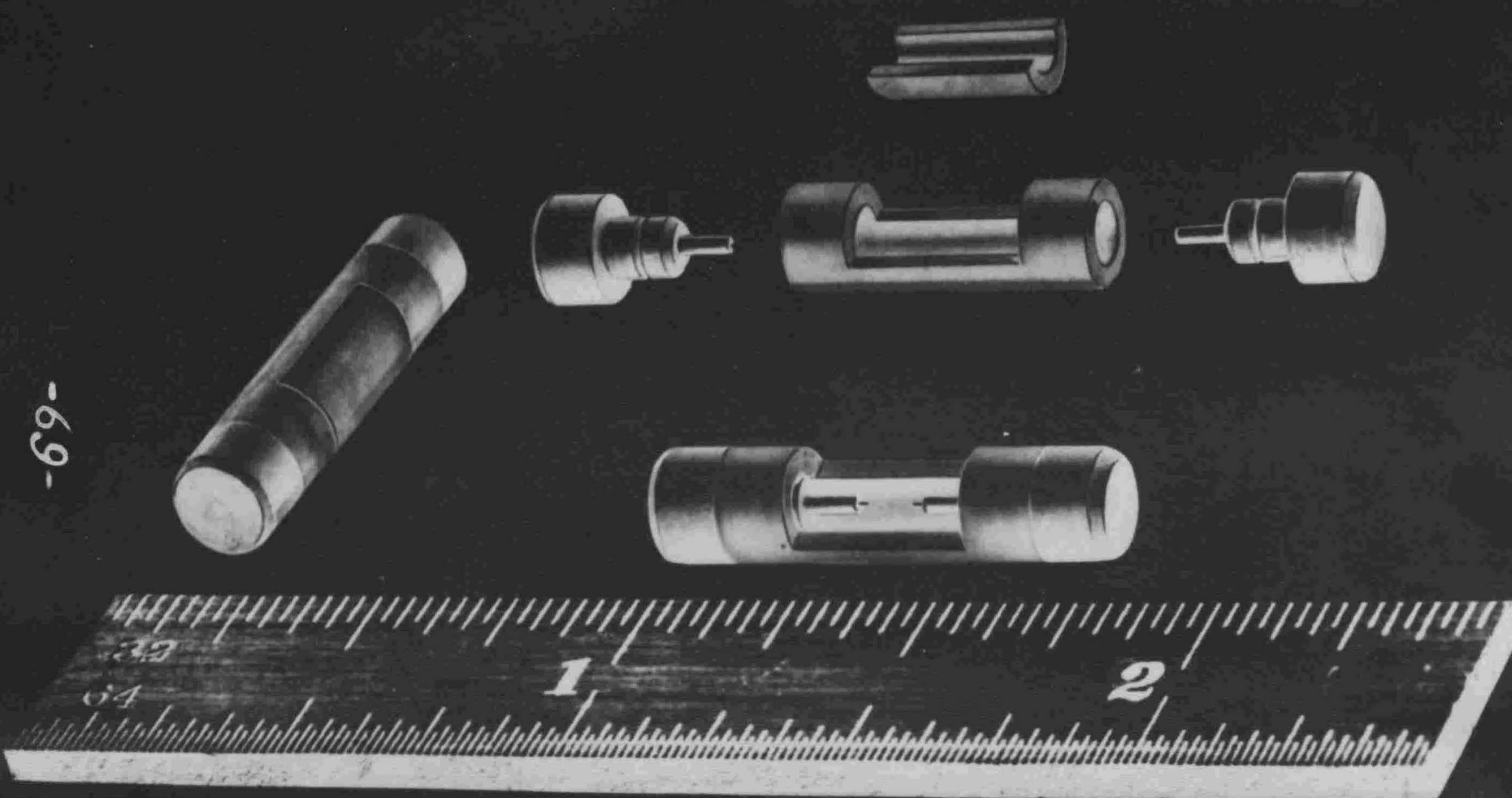
Figure I.

Comparison of Power Sensitivity in Typical Load Lamp



SPERRY TYPE 821 BARRETTER

FIGURE II.



SPERRY TYPE 821 BARRETTER - PHYSICAL COMPONENTS

FIGURE III.

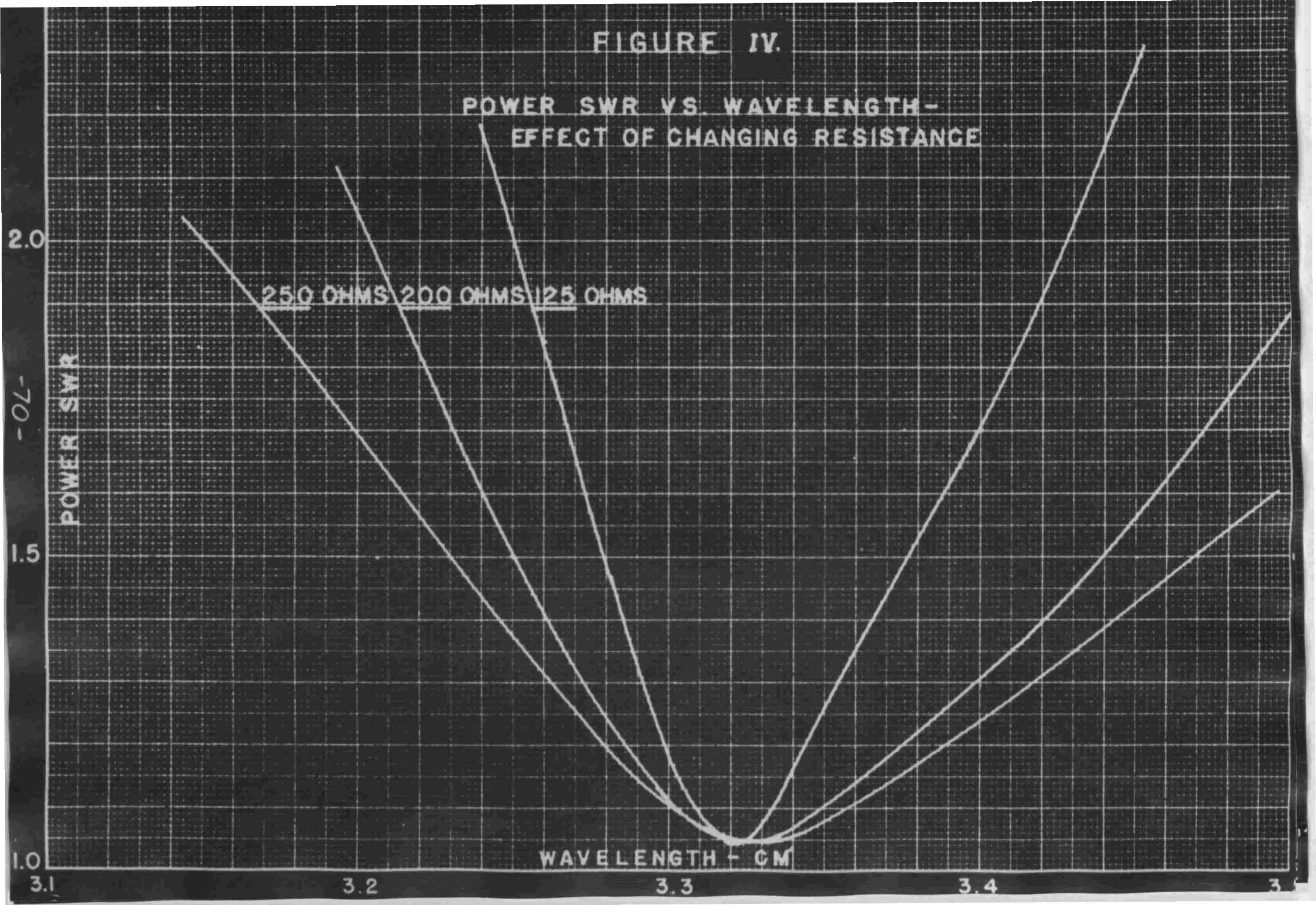


FIGURE IV.
POWER SWR VS. WAVELENGTH -
EFFECT OF CHANGING RESISTANCE
250 OHMS
200 OHMS
125 OHMS
POWER SWR
2.0
1.5
1.0
WAVELENGTH - CM
3.1
3.2
3.3
3.4
3.

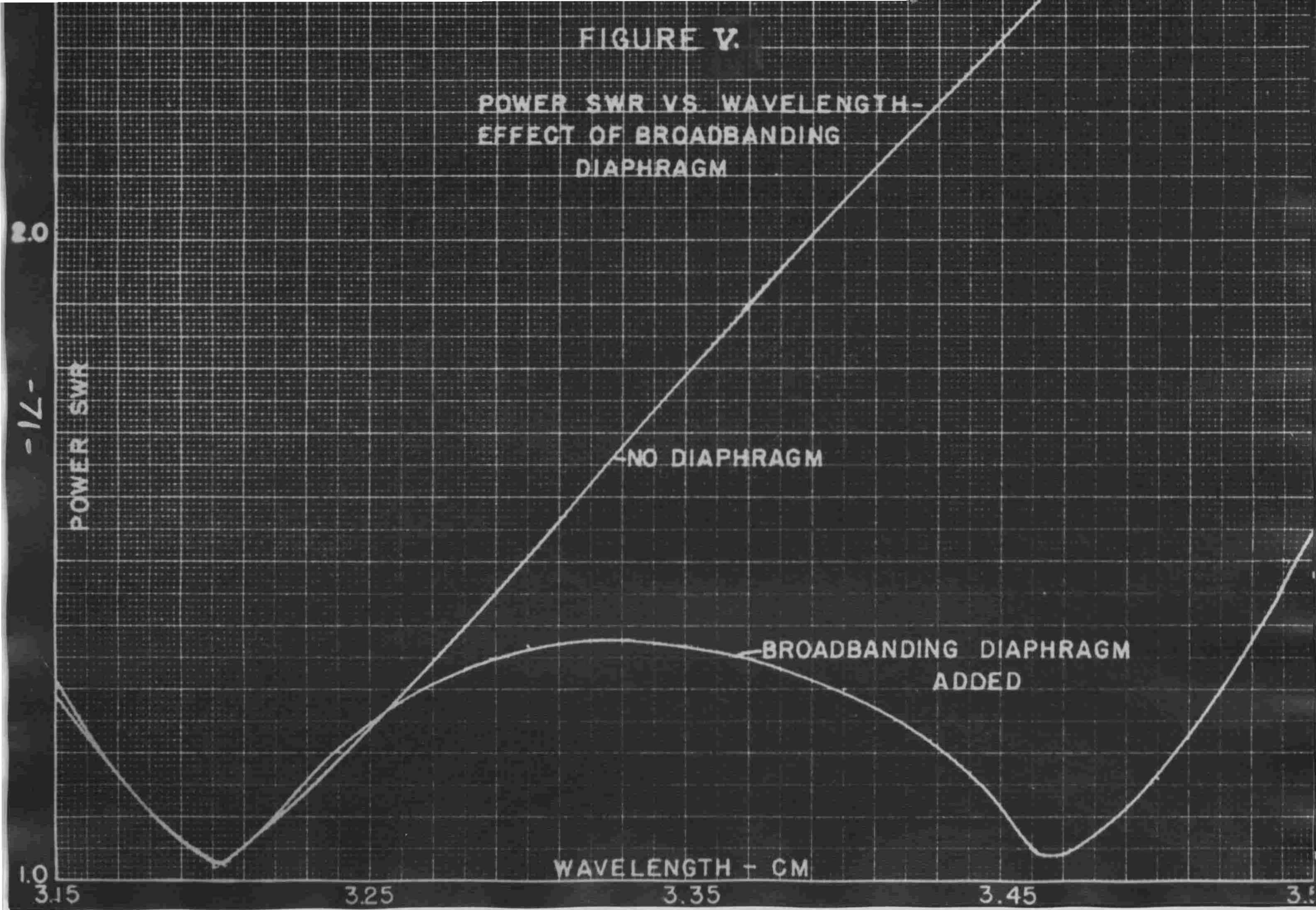
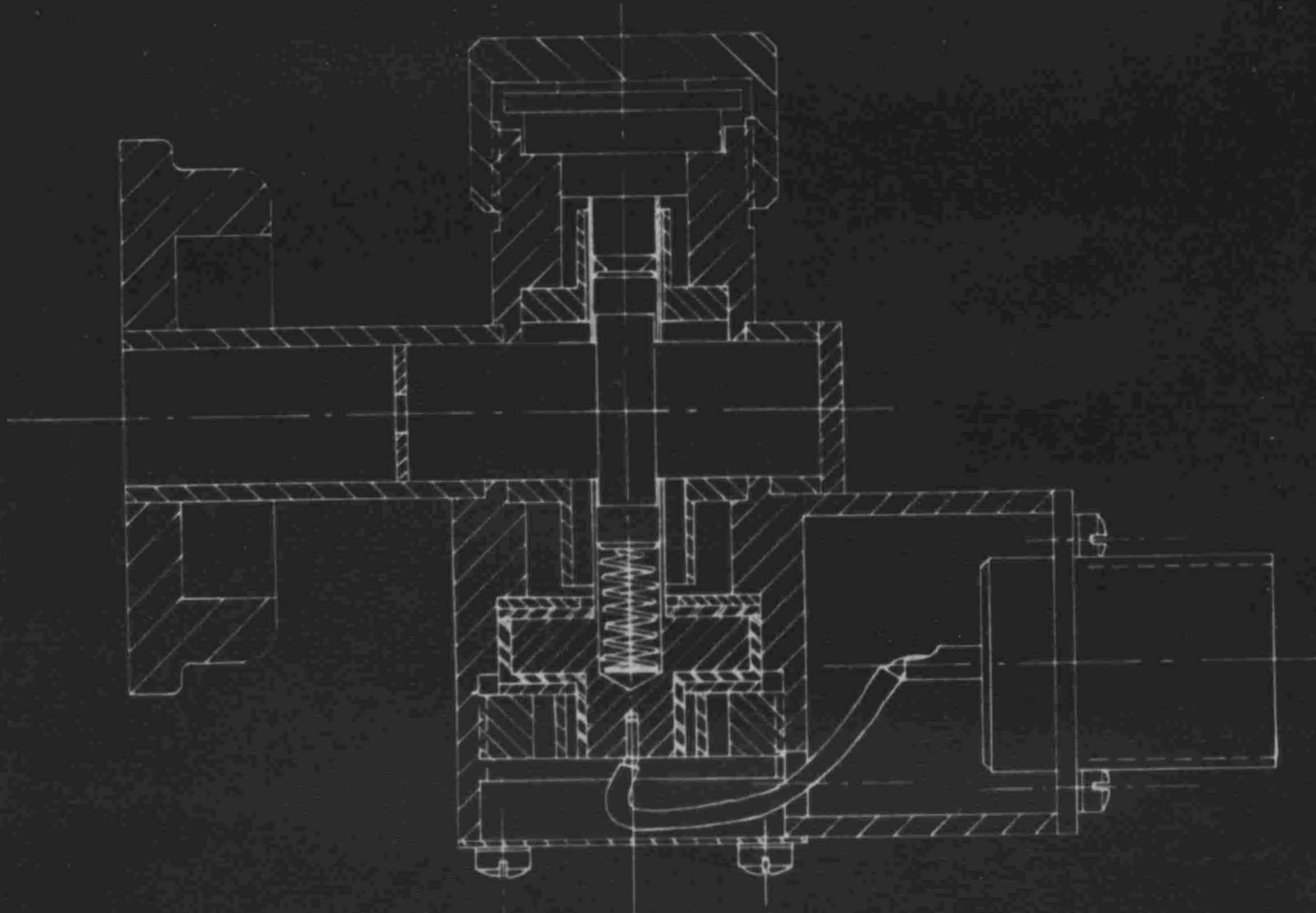


FIGURE V.

POWER SWR VS. WAVELENGTH-
EFFECT OF BROADBANDING
DIAPHRAGM

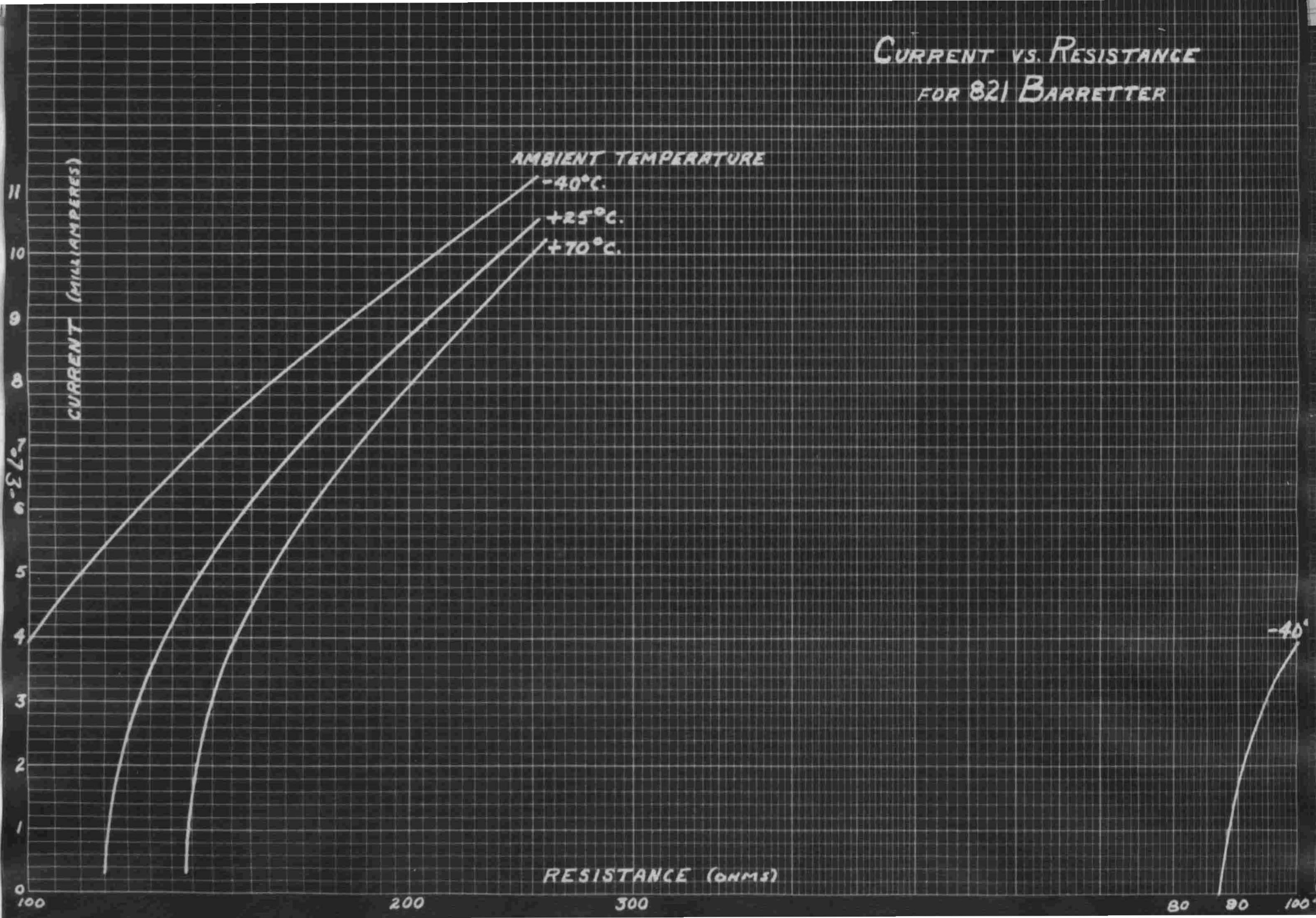


TYPE 82X MOUNT

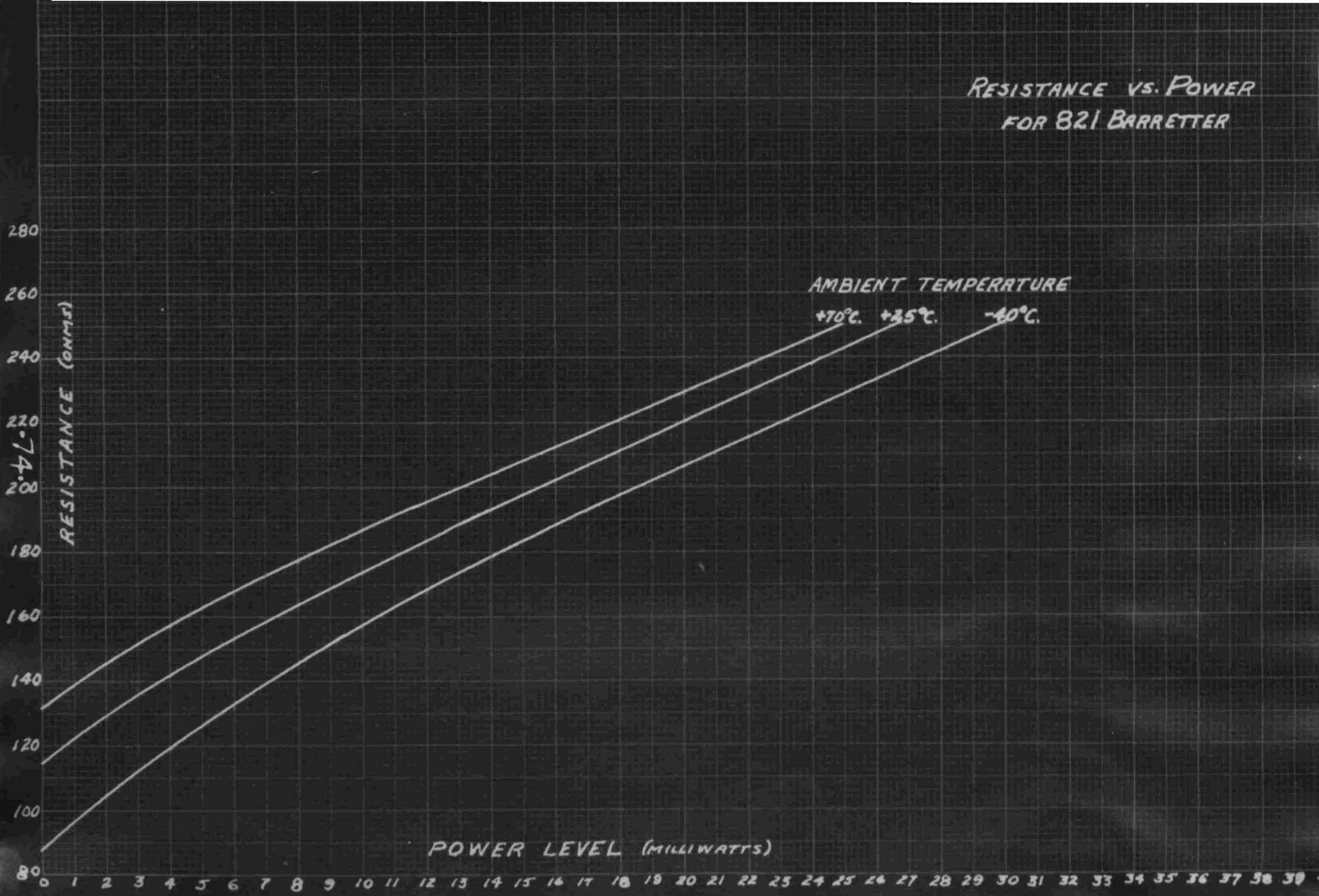
CROSS SECTION VIEW

APPROX. DOUBLE SIZE

FIGURE VI.



CURRENT VS. RESISTANCE
FOR 821 BARRETTER
AMBIENT TEMPERATURE
-40°C.
+25°C.
+70°C.
-40°
CURRENT (MILLIAMPERES)
RESISTANCE (OHMS)
0
1
2
3
4
5
6
8
9
10
11
100
200
300
80
90
100


RESISTANCE VS. POWER
FOR 821 BARRETTER
AMBIENT TEMPERATURE
+70°C.
+25°C.
-40°C.
RESISTANCE (OHMS)
280
260
240
220
200
180
160
140
120
100
80
POWER LEVEL (MILLIWATTS)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
FIGURE VIII.

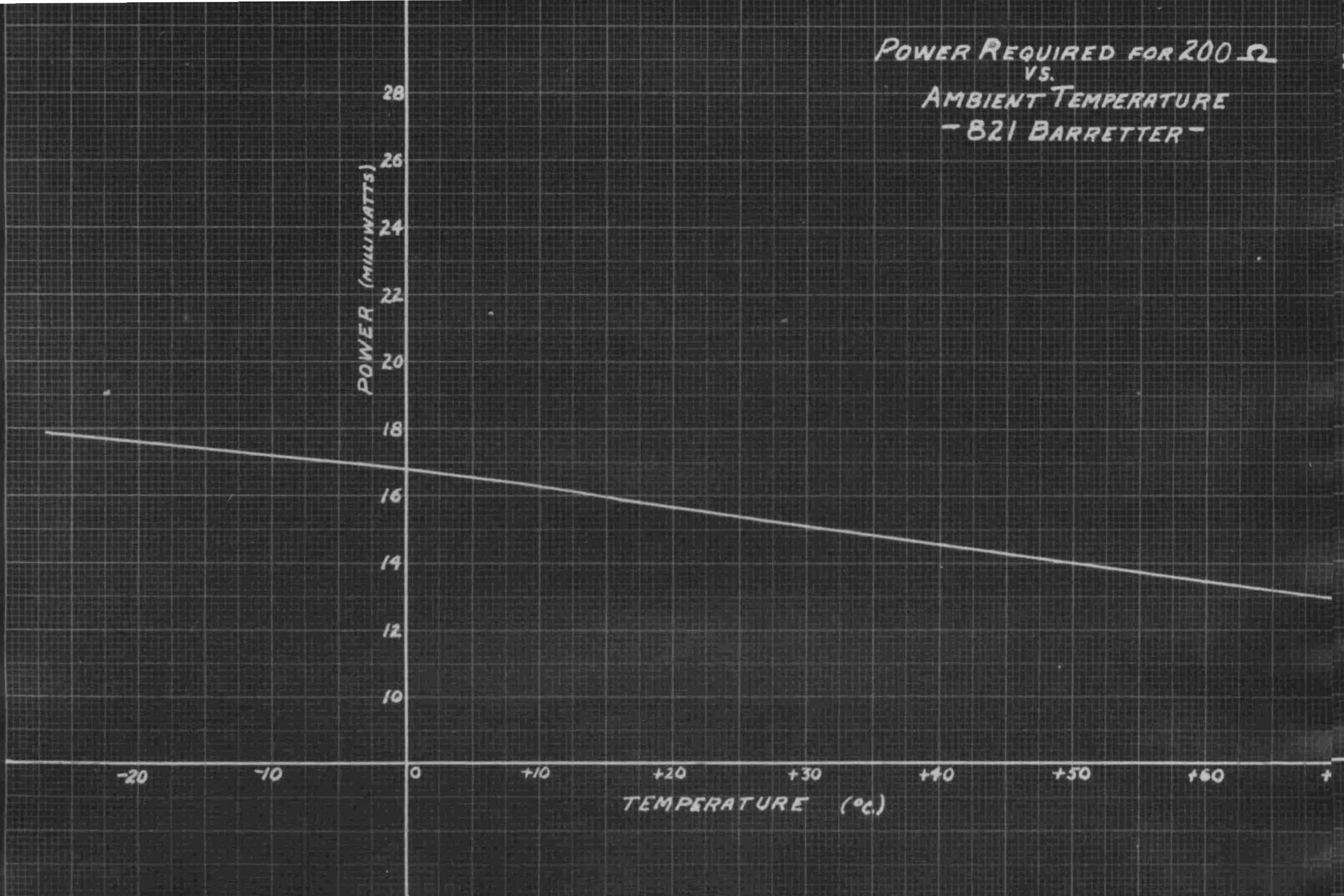

POWER REQUIRED FOR 200 Ω
VS.
AMBIENT TEMPERATURE
- 821 BARRETTER -
POWER (MILLIWATTS)
28
26
24
22
20
18
16
14
12
10
-20
-10
0
+10
+20
+30
+40
+50
+60
TEMPERATURE (°C.)

FIGURE IX.

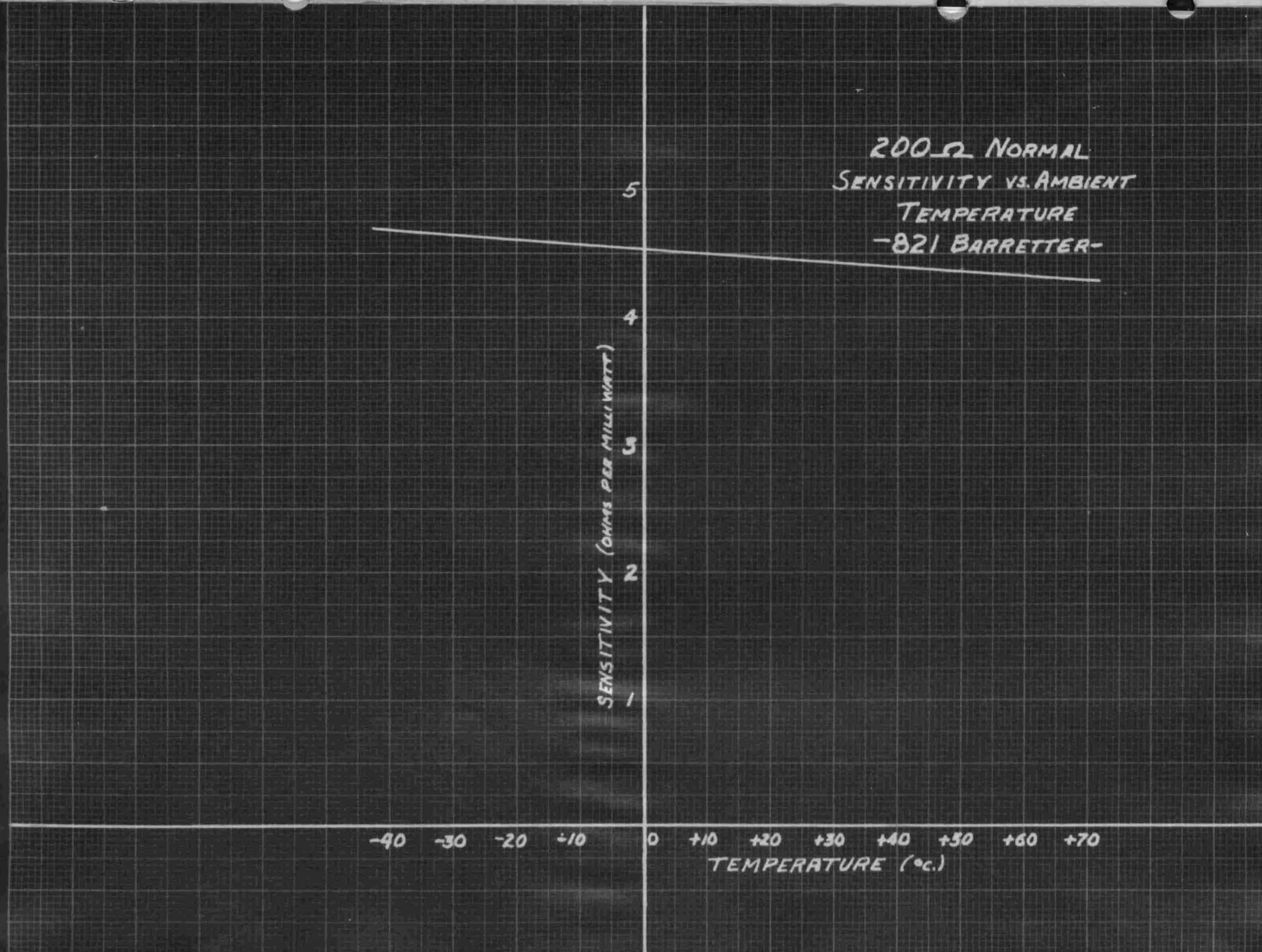

200 Ω NORMAL
SENSITIVITY VS. AMBIENT
TEMPERATURE
-821 BARRETTER-
SENSITIVITY (OHMS PER MILLIWATT)
1
2
3
4
5
-40
-30
-20
-10
0
+10
+20
+30
+40
+50
+60
+70
TEMPERATURE (°C.)

FIGURE X.

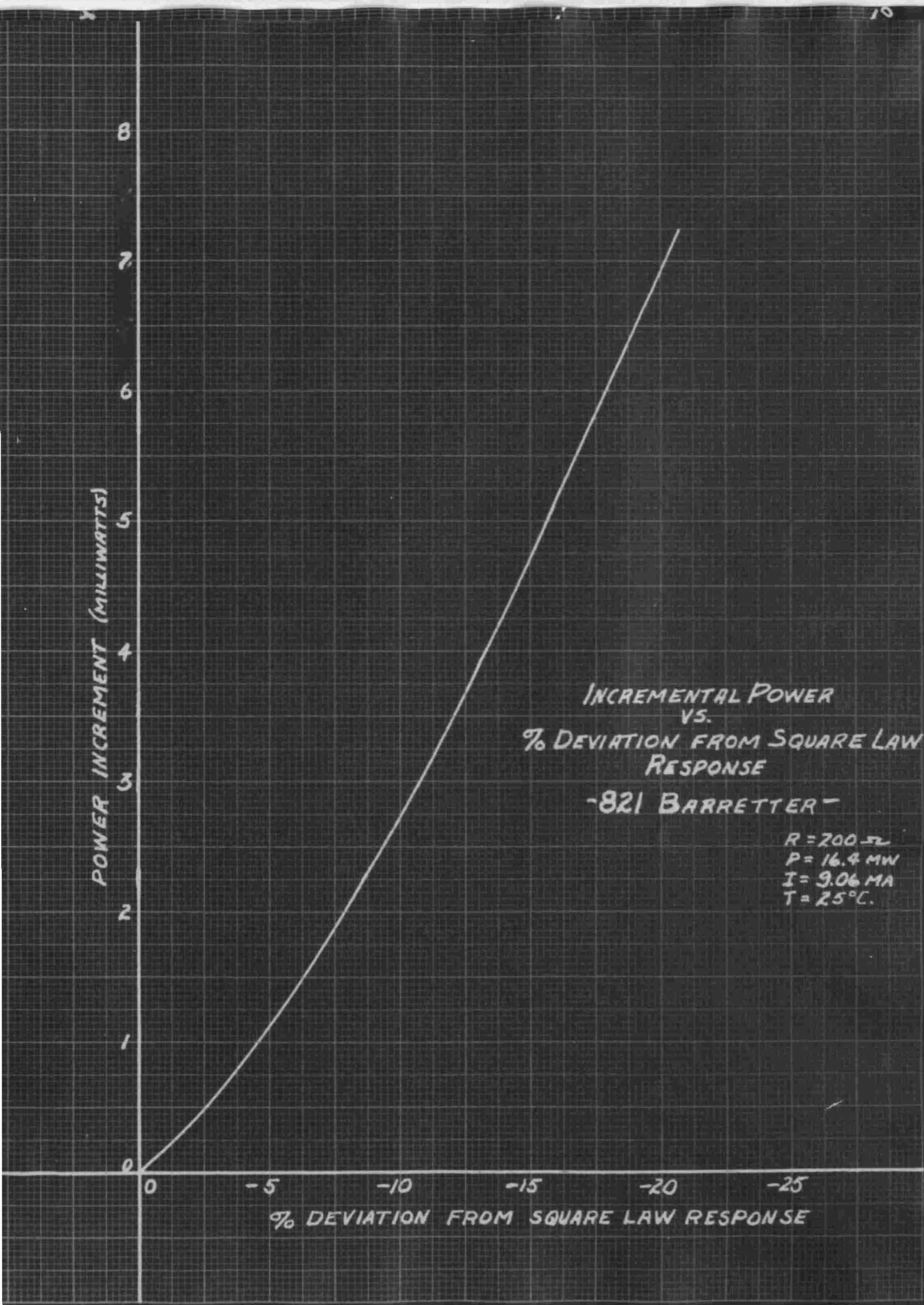

INCREMENTAL POWER
VS.
% DEVIATION FROM SQUARE LAW
RESPONSE
-821 BARRETTER-
R = 200 Ω
P = 16.4 MW
I = 9.06 MA
T = 25°C.
POWER INCREMENT (MILLIWATTS)
% DEVIATION FROM SQUARE LAW RESPONSE
0
1
2
3
4
5
6
7
8
-5
-10
-15
-20
-25

FIGURE XI.

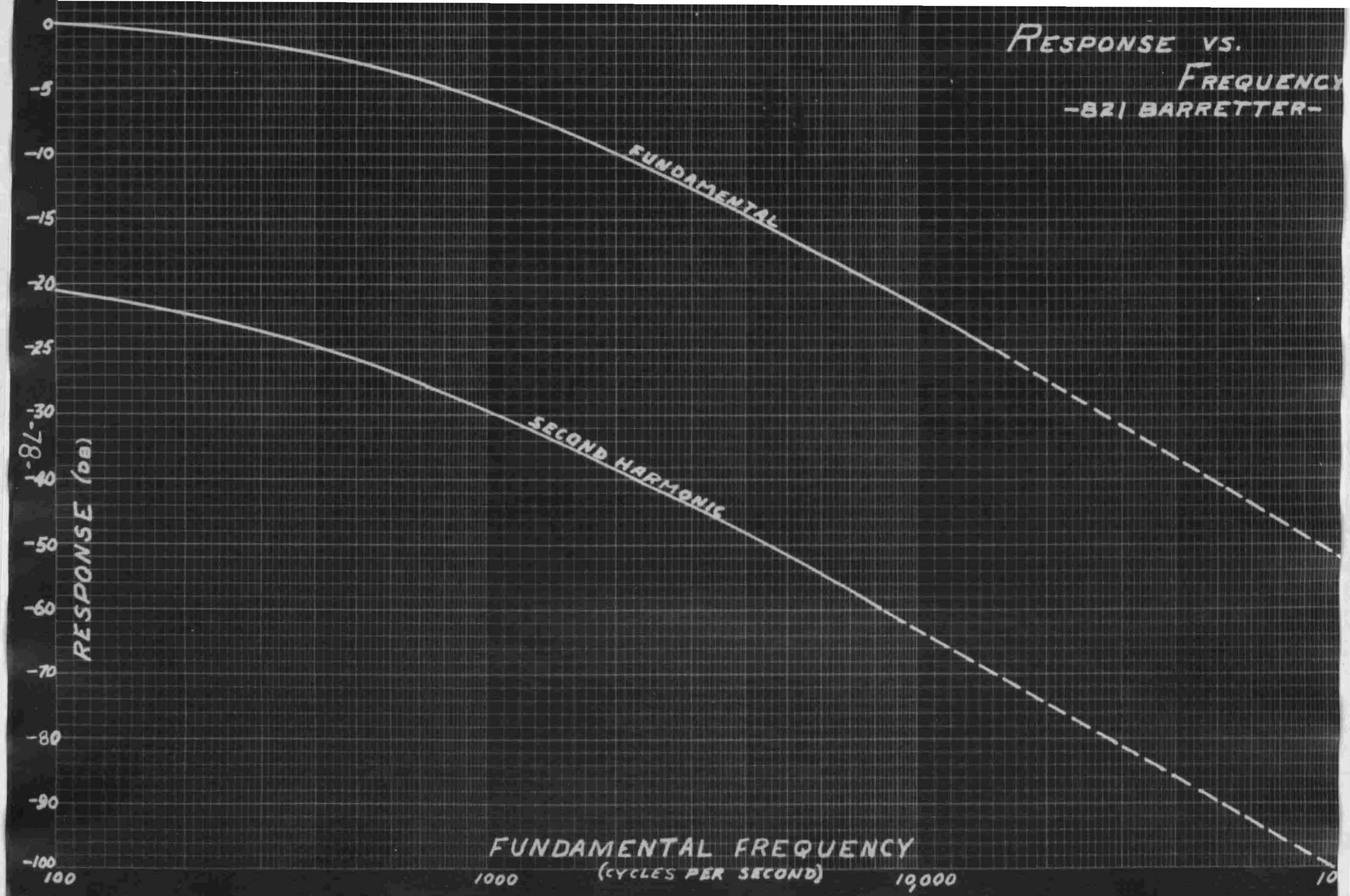
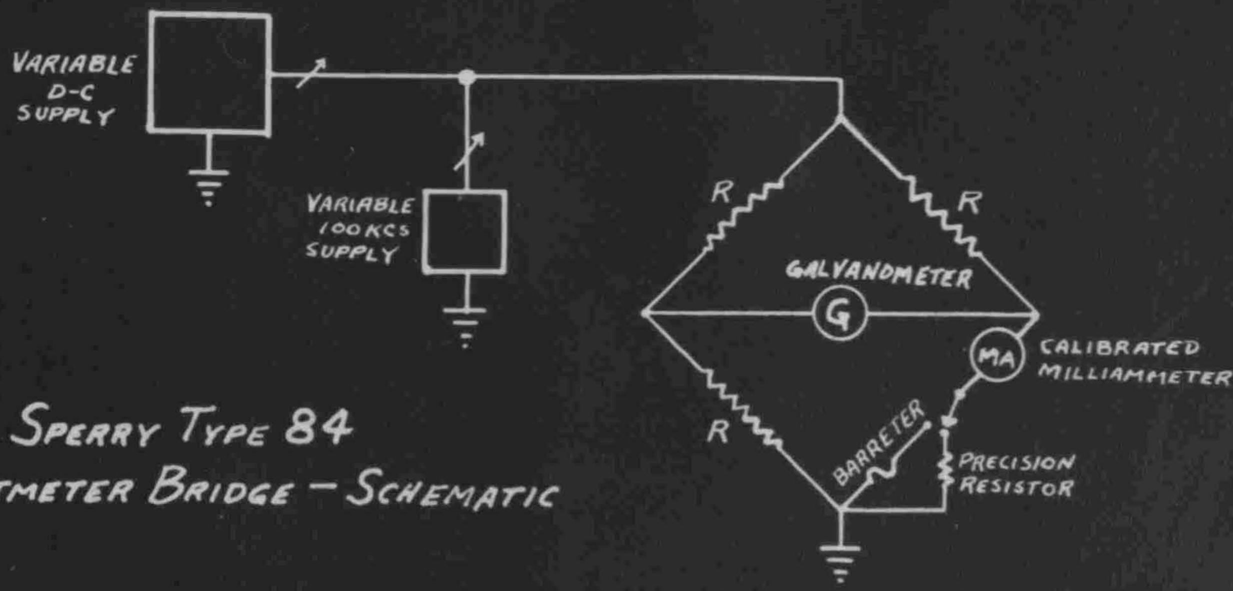
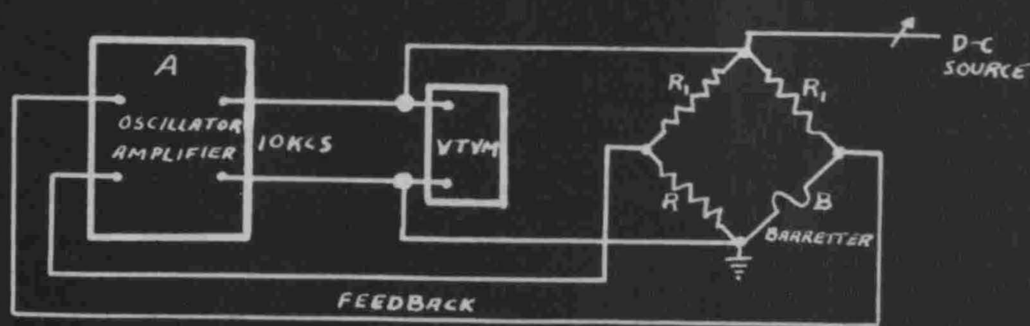

RESPONSE VS. FREQUENCY
-821 BARRETTER-
FUNDAMENTAL
SECOND HARMONIC
RESPONSE (DB)
0
-5
-10
-15
-20
-25
-30
-40
-50
-60
-70
-80
-90
-100
FUNDAMENTAL FREQUENCY
(CYCLES PER SECOND)
100
1000
10,000
10

FIGURE XII.



SPERRY TYPE 84
WATTMETER BRIDGE – SCHEMATIC

FIGURE XIII.



SPERRY TYPE 123 WATTMETER BRIDGE
– SCHEMATIC –

FIGURE XIV.